N7878857

(NASA-CR-157748) DESIGN, MANUFACTURE, DEVELOPMENT, TEST, AND EVALUATION OF BORON/ALUMINUM STRUCTURAL COMPONENTS FOR SPACE SHUTTLE. VOLUME 2: MATERIALS AND PROCESSING (General Dynamics/Convair) 187 p 00/24 Unclas 34453

REPORT NO. GDCA-DBG73-006
CONTRACT NAS 8-27738

DESIGN, MANUFACTURE, DEVELOPMENT, TEST, AND EVALUATION OF BORON/ALUMINUM STRUCTURAL COMPONENTS FOR SPACE SHUTTLE

VOLUME II ✦ MATERIALS AND PROCESSING

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August 1973

Prepared Under
Contract NAS8-27738

Submitted to
National Aeronautics and Space Administration
GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

Prepared by
CONVAIR AEROSPACE DIVISION OF GENERAL DYNAMICS
San Diego, California

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74-10012

FOREWORD

The following final report describes work performed on NASA Contract NAS 8-27738 by the San Diego Operation, Convair Aerospace Division of General Dynamics Corporation. The work was administered by the Materials Division of the Astronautics Laboratory, George C. Marshall Space Flight Center, Huntsville, Alabama 35812. Mr. F. P. LaIacona was the NASA project officer.

The program was conducted by the Advanced Composites Group at Convair Aerospace, San Diego Operations. Pricipal designers for the program were A. F. Fujimoto, W. F. Wennhold, and R. E. Eckberg; the shear beam component fabrication was directed by A. R. Robertson, and the compression panel component fabrication was directed by C. R. Maikish. Other primary contributors to the program were:

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This report covers the entire program contract from 1 July 1971 to 30 June 1973.

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ABSTRACT

A program was performed to evaluate material properties, processing techniques, and fabrication characteristics of boron/aluminum (B/Al) to develop sufficient technology to permit the application of B/Al in reusable spacecraft with a high degree of confidence. The program included the design of three thrust structure components for the space shuttle, the testing of subcomponent specimens to verify design and joint fabrication concepts, and culminated in the design and fabrication of two components: a 1 by 0.96m (40 by 38 in.) shear beam weighing 35.4 kg (78 lb) and designed for service at 366K (200F), and a 2 by 0.7m (80 by 29 in.) compression panel weighing 20.2 kg (44.4 lb) and capable of service up to 589K (600F). These structures successfully demonstrated that B/Al structural components could be fabricated and assembled using modified sheet metal technology and today's factory equipment. These panels have been shipped to NASA-MSFC where the shear beam will be structurally tested at room temperature and the compression panel at 589K (600F).

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SECTION 1

INTRODUCTION

The application of advanced composites, both resin and metal-matrix, to aircraft and missile structure has become prevalent in recent years. It is clear that these high-strength, low-weight composite materials will find additional structural applications on future aerospace vehicles.

Several large aircraft and missile components have already been fabricated using metal-matrix composites as one of the key structural materials. The PRIME adapter for the Atlas booster (Reference 1), built in 1968, was the first major metal-matrix structure built: 1.2m (4 ft) in diameter and 2.1m (7 ft) high. During testing, failure (crippling of three stringers) occurred at 133% of ultimate design load (200% of limit load). The F-106 aircraft access door (Reference 2), built in 1969, was the first boron/aluminum (B/Al) structure to be flight tested. A duplicate test panel failed at 169% of design limit load. An F-111 aircraft fuselage bulkhead (Reference 3) consisted of BORSIC/6061-T6 Al with a titanium frame. The crossplied skin was stiffened with unidirectional zees, angles, and straight and joggled tees. During structural testing, failure occurred at 130% of design ultimate load. A dual OV1 support system truss structure (Reference 4), approximately 2m (80 in.) long and 0.8m (30 in.) square, was fabricated from seamless BORSIC/aluminum tubes. The spacer skins for the same system were fabricated from roll-formed crossplied skins 3.1m (10 ft) in length.

These test articles demonstrated that B/Al technology had progressed sufficiently to enable consideration of its use for space shuttle applications. Fabrication methods and joining techniques had been thoroughly examined and it was only necessary to optimize joining processes for large-scale structures, and to demonstrate the capability of metal-matrix structures to withstand the loading and environmental conditions encountered in space shuttle applications.

1.1 PROGRAM OBJECTIVES

The objectives of this program were to compare the use of B/Al in Space Shuttle application with other structural materials and to evaluate material properties, processing techniques, and fabrication characteristics of B/Al to develop sufficient technology to permit application of B/Al for space shuttle structural components with a high degree of confidence.

The program objective of demonstrating the applicability of B/Al composite structures for reusable spaceflight vehicles was achieved through a series of logical processes. It started with selecting and characterizing materials and proceeded with developing minimum design allowable data. Coincidental with this study, design and structural analysis of three structures were performed. Fabrication processes applicable to the production of large-scale, metal-matrix structures were optimized, and selected subcomponents of a thrust structure shear web beam and a uniformly loaded compression panel were fabricated and tested to verify design and structural analysis, and to demonstrate the ability of developed joining methods to withstand both thermal and load cycling. A full-thickness component of the thrust structure shear web beam and a uniformly loaded compression panel were designed and fabricated for testing at MSFC.

The most significant accomplishment on the program was the successful fabrication of metal-matrix structures applicable to the space shuttle. These structures utilized such diverse sheet metal fabrication processes as forming, welding, brazing, drilling, sawing, riveting and heat treating of unidirectional and crossplied B/Al ranging in thickness from 1.78 mm (0.070 in.) to over 15.3 mm (0.60 in.). The two component test articles, a 1.0 × 0.96m (40 × 38 in.) shear beam and a 2.03 × 0.74m (80 × 29 in.) compression panel, demonstrated that B/Al structures similar to those required for reusable space flight vehicles could be fabricated with existing aircraft shop facilities using modified sheet metal technology.

1.2 ORGANIZATION

This report is divided into two volumes. The first volume details the design, stress analysis, and testing of structures examined during the program. Specifically, designs are presented for 9.2 × 3.1m (30 × 10 ft) and 1.0 × 0.96m (40 × 38 in.) shear beams, a 9.2 × 3.1m (30 × 10 ft) truss, and 3.1 × 3.1m (10 × 10 ft) and 2.0 × 0.7m (80 × 29 in.) compression panels as well as several subcomponent specimens. The second volume contains material characterization, process development, process and material specifications or guidelines, and manufacturing procedures used in the fabrication of component and subcomponent test articles.

1.3 COMPONENT TESTING

The two major component test specimens prepared during the program, a 1 × 0.96m (40 × 38 in.) shear beam and a 2 × 0.75m (80 × 29 in.) compression panel, are to be tested at NASA-MSFC. Because of scheduling difficulties at the Marshall Space Flight Center, it was not possible to perform these tests prior to issuance of this document. At the time of publication, no firm date had been established for testing the two components.

1.4 NEW TECHNOLOGY

In compliance with the New Technology clause of this contract, personnel assigned to work on the program were advised, and periodically reminded, of their responsibilities in the prompt reporting of items of New Technology. In addition, reports generated as a result of the contract work were reviewed by the Program Manager as a further means of identifying items to be reported.

Response was made to all inquiries by the company-appointed New Technology Representative, and when deemed appropriate, conferences were held with the New Technology Representative to discuss new developments arising out of current work that could lead to New Technology items. The New Technology Representative has the responsibility for transmitting reportable items of New Technology to the Technology Utilization Officer, as well as the annual and final reports specified in the Clause.

The Contractor believes the performance of personnel associated with the contract has been consistent with the requirements of the New Technology clause.

SECTION 2

MATERIALS EVALUATION

The primary objective of the materials evaluation phase was to determine the mechanical properties of boron/aluminum composite material to enable the establishment of minimum design values that could be used with assurance in high-integrity structures. Additional objectives were to perform an initial materials assessment and selection, to evaluate the effects of heat treatments on mechanical properties, to determine corrosion susceptibility and develop protective methods for large-diameter boron/aluminum composites and to perform quality assurance testing. The materials evaluation phase consisted of five tasks: 1) materials assessment, 2) heat treatment, 3) materials evaluation, 4) corrosion studies, and 5) quality assurance testing.

2.1 MATERIALS ASSESSMENT

The materials assessment task was performed to select the composite materials for test evaluation, fabrication studies, and hardware fabrication. The following sections describe the objectives, background, test materials and procedures, and results for the materials assessment task.

2.1.1 TASK OBJECTIVES. The primary purpose of this task was to perform an initial assessment on the commercially available, large-diameter boron/aluminum composite materials that appeared to possess the desired properties for Space Shuttle structural applications. This assessment was accomplished through the collection of existing data on materials supplied by various vendors and on data generated by Convair Aerospace as an initial effort on the program. Materials were restricted to boron/aluminum composites with a minimum filament diameter of 142 μm (5.6 mils). The materials assessment task included a study of the various filament sizes and coatings, aluminum alloy matrices, volume percentages of filaments, layups, and primary composite processing methods and techniques. Test panels of the most promising materials were procured and tested to verify vendor claims and previous test results. The test program consisted of longitudinal and transverse tensile and shear tests performed at room and elevated temperatures.

2.1.2 BACKGROUND. The commercial development of large-diameter boron filaments, 142 μm (0.0056 inch) diameter as compared to the standard 101 μm (0.004 inch) diameter, and their use in processing of boron/aluminum composite material has resulted in considerable improvements in mechanical properties and substantial reductions in material costs.

Prior to this program, Convair Aerospace had processed and evaluated ten panels of the large-diameter boron/aluminum composite material. Various starting materials (diffusion-bonded monolayer tapes, plasma-sprayed tapes, and continuously cast tapes) and processing methods (high-pressure gas autoclave diffusion bonding and low-pressure braze bonding) were included in the evaluation. Each of the panels exhibited considerably higher longitudinal tensile strength properties than the standard boron/aluminum composite material as can be seen in the brief summary of properties given in Table 2-1.

Table 2-1. Properties of Large-Diameter Boron/Aluminum Composite Material

Composite Tape	Processing Method	V/O	F_{tu} MN/m^2 (ksi)	E GN/m^2 (msi)
Diffusion-bonded Monolayer	Diffusion bonded	44.1	1240 (178)	214 (30.9)
Plasma Sprayed (UCC)	Diffusion bonded	49.3	1390 (201)	211 (30.5)
Plasma Sprayed (HS)	Diffusion bonded	53.4	1410 (203)	240 (34.7)
Continuously Cast	Diffusion bonded	55.0	1390 (201)	263 (38.0)
Continuously Cast	Brazed	55.0	1450 (209)	256 (37.0)
Continuously Cast	As-received	70.0	1650 (238)	298 (43.0)
Small-diameter Boron/ Aluminum		50.0	1150 (166)	222 (32.0)

In addition to substantial improvements in longitudinal strength properties (8 to 43% depending upon volume percent), the use of large-diameter boron filaments also resulted in improved transverse strength properties and, more importantly, a reduction in the scatter of the test data. The scatter in tensile strength properties for the large-diameter boron/aluminum composite material was only about ± 15% as compared to ± 20% for previous material. The reduced scatter enables calculation of much higher design allowables and enhances confidence in the material.

The use of large-diameter boron/aluminum composite material also resulted in cost reductions of 20 to 40%. The reduced composite material costs resulted from lower filament costs (about 30%) and lower layup and processing costs (about 20%). Therefore, the use of large-diameter boron filaments in advanced metal matrix composite materials results in substantially improved properties and lower costs. It was, therefore, believed that the improved, large-diameter boron/aluminum composite materials should be seriously considered for primary aerospace structural applications.

Based on Convair Aerospace and vendor experience (References 1 through 9), it was anticipated that the average mechanical properties of large-diameter boron/aluminum (B/Al) composite material would be as shown in Table 2-2.

Table 2-2. Anticipated Mechanical Properties of Large-Diameter B/Al Composite Material

Property	Direction	Condition	RT Strength MN/m^2 (ksi)	RT Modulus GN/m^2 (msi)	Poisson's Ratio
Tensile	Long.	F or ST&A*	1310 (190 ± 15)	220 (32 ± 2)	0.230 ± 0.030
Tensile	Trans.	F	83 (12 ± 4)	138 (20 ± 2)	0.130 ± 0.020
Tensile	Trans.	ST&A	165 (24 ± 4)	138 (20 ± 2)	
Compr.	Long.	F	2720 (250 ± 25)	138 (20 ± 2)	
Compr.	Long.	ST&A	2900 (275 ± 25)	235 (34 ± 2)	
Compr.	Trans.	F	207 (30 ± 5)	152 (22 ± 2)	
Compr.	Trans.	ST&A	240 (35 ± 5)	152 (22 ± 2)	
Shear		F	83 (12 ± 4)	41 (6 ±1)	
		ST&A	165 (24 ± 4)	41 (6 ±1)	
Fatigue	Long.	F or ST&A	Runout (10^7 cycles) at 70% of F_{tu}		
Fatigue	Trans.	F	Runout (10^7 cycles) at 30% of F_{tu}		
Fatigue	Trans.	ST&A	Runout (10^7 cycles) at 50% of F_{tu}		

For all properties at 366K (200F) substract 10% of RT properties

Ply thickness = 1.5 mm (0.062 in.)
*F = as received
ST&A = solution treated and aged

2.1.3 TEST MATERIALS AND PROCEDURES. Two 142 μm (5.6 mil) boron/6061 aluminum diffusion bonded composite test panels were procured from the material supplier, Amercom, Inc. The test panels were identified as MA-1 and MA-2. Each measured 0.30 by 0.30 meter (12 by 12 inches).

Quality assurance testing consisted of nondestructive evaluation, visual observations, thickness measurements, volume percent determinations and metallographic examination. Results of nondestructive testing are given in Section 2.5. Visual observations indicated good quality material. There were no visual surface defects nor indications of internal defects. Thickness measurements indicated 1.42 ± 0.05 millimeters (0.056 ±0.002 inch) for panel MA-1 and 1.45 ±0.07 millimeters (0.057 ±0.003 inch) for panel MA-2. Volume percent determinations were made by the leaching method (i.e., weighing a sample of B/Al, leaching away the aluminum and reweighing the dried boron filaments as thoroughly described in Reference 1).

Results were 57.7 V/O for MA-1 and 46.0 V/O for MA-2. Panel MA-1 was very close to its nominally intended 58 V/O; however, panel MA-2 had a much lower V/O than was intended (52 V/O). A discussion was held with the supplier, and on rechecking records and raw materials it was determined that the aluminum foils used in panel MA-2 were too thick. A metallographic examination was performed on panels MA-1 and MA-2. Results verified the volume percent determination and indicated well bonded material, as can be seen from the photomicrographs (Figures 2-1 and 2-2).

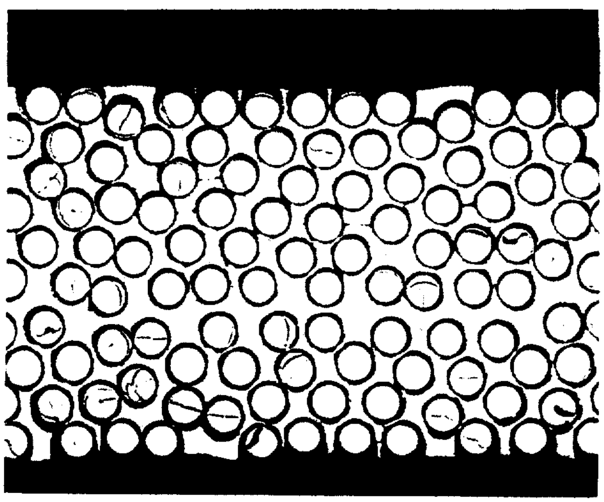


Figure 2-1. Photomicrograph of B/Al Composite Panel MA-1 (58 V/O) (D236)

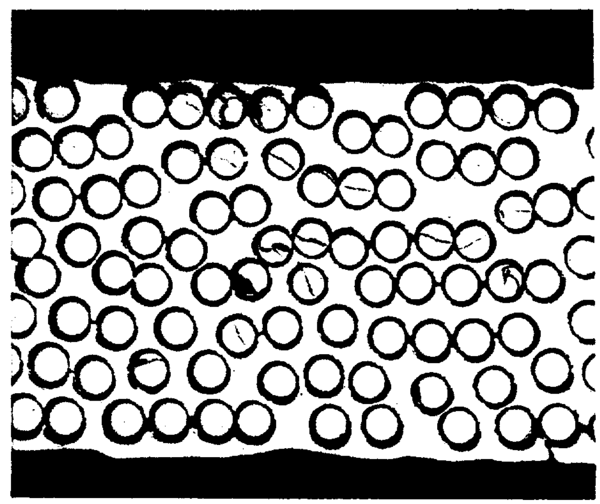


Figure 2-2. Photomicrograph of B/Al Composite Panel MA-2 (46 V/O) (D237)

The composite test panels were cut into specimen blanks. Doublers were bonded to longitudinal and transverse tensile specimens. Shear specimens were machined by electrical discharge machining (EDM). All test specimens were individually identified, inspected, and measured prior to testing. Configuration and size of test specimens are shown in Figure 2-3.

Mechanical property testing consisted of longitudinal and transverse tensile and shear tests performed at room and elevated temperatures. Tests were performed on an Instron universal testing machine. Stress/strain curves were obtained with extensometer and/or strain gages.

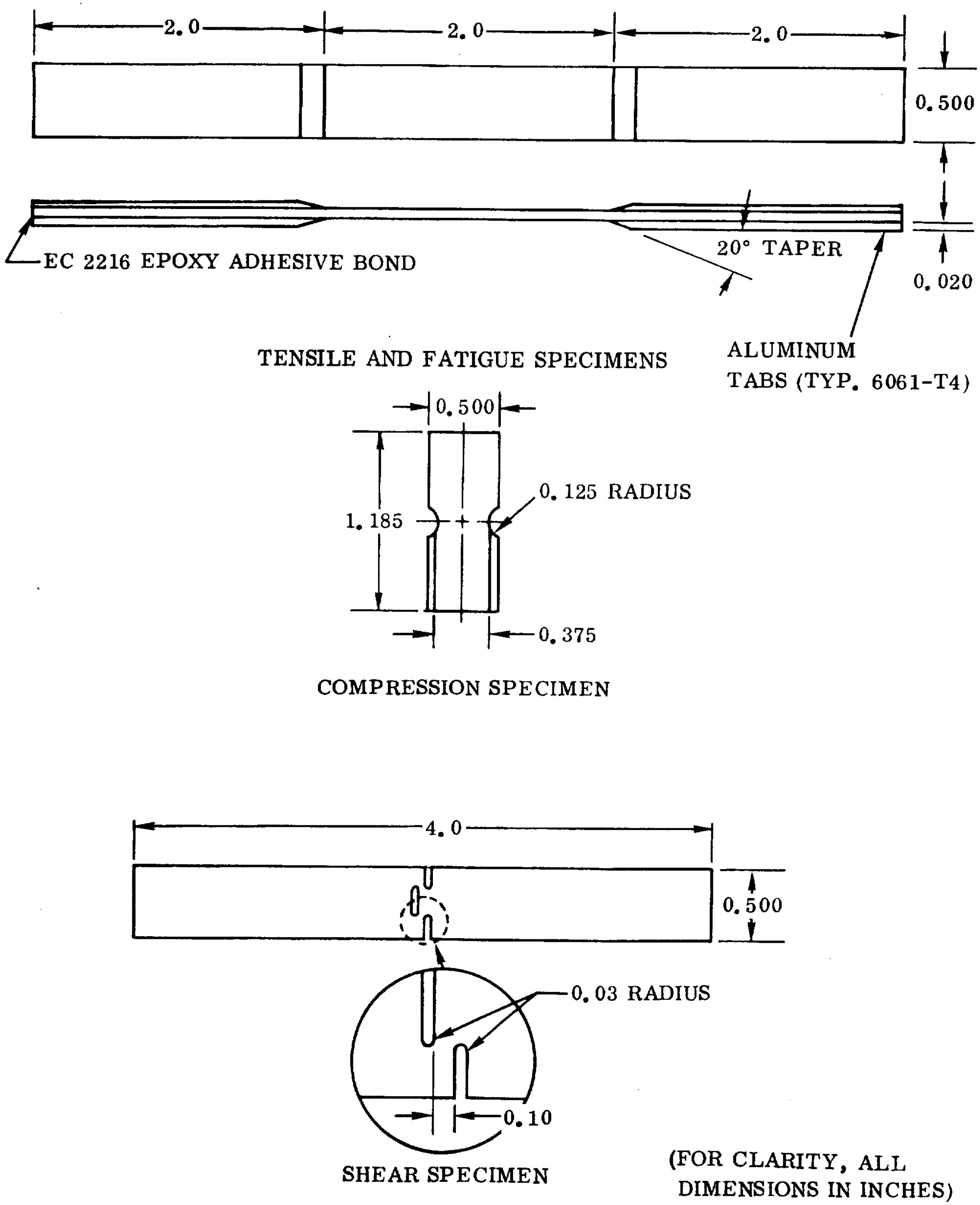


Figure 2-3. Test Specimens

2.1.4 TEST RESULTS. The test results are given in Table 2-3. Longitudinal tensile strengths exceeded expectations while transverse tensile and shear strengths were normal for B/Al material. However, tensile modulus values for both longitudinal and transverse material were lower than expected. Both the longitudinal and transverse tensile specimens exhibited excellent strains to failure at room temperature. As expected, the composite panel with the higher volume percent of boron filaments had the higher longitudinal tensile strength and modulus; whereas, the lower volume percent panel showed slightly higher transverse tensile and shear strength properties. Tests at elevated temperatures resulted in significant decreases in transverse tensile and shear strengths with little or no effect on longitudinal strength and modulus properties.

Analysis of these test data and previous results obtained on large diameter B/Al composites resulted in the recommendation that material selected for allowables testing and process development consist of 142 μm (5.6 mil) boron/6061 aluminum diffusion bonded, with 53 ±2 V/O for unidirectional layups and 50^{+2}_{-1} V/O for 0-90° (or ± 45°) layups. These material selections were believed to provide or exceed the minimum design requirements for material properties.

2.2 HEAT TREATMENT

The effects of two different thermal treatments were determined on three unidirectional and one ±45° crossplied B/Al composite panels.

2.2.1 OBJECTIVES. The primary objective of the heat treatment task was to determine the effects of various thermal treatments on the mechanical properties of B/Al composite material. It was hoped that solution treating and aging would improve transverse tensile and shear strength properties, and that solution treating plus cryogenic soaking and aging would enhance longitudinal properties as well as transverse properties.

2.2.2 BACKGROUND. Convair Aerospace had found that the properties of boron/aluminum composite materials could be considerably improved by various thermal treatments (References 1 through 4). Fifty to 100% increases in transverse tensile and shear strengths are typical for 50 V/O B/6061 Al as a result of solution treating and aging. Recent improvements in longitudinal properties have been obtained by immersion in liquid nitrogen after solution treating and prior to aging. The increase in longitudinal tensile strength (5 to 10% typically) is believed to be due to grain refinement and reduction of residual stresses.

2.2.3 TEST MATERIALS AND PROCEDURES. Specimen blanks from composite panels MA-1, MA-2, ME-2, and MEX-1 were subjected to two different thermal treatments. Half of the blanks were solution treated and aged; the others were solution treated plus cryogenic soaked plus aged. In each case, the solution treatment consisted of 30 minutes at 799K (980F) followed by a water quench. Aging was performed at 450K (350F) for eight hours. The cryogenic soak consisted of five minutes in liquid

Table 2-3. Mechanical Properties of B/Al Composite Materials (Material Assessment)

Panel	Test Temperature K	Test Temperature (F)	Direction	Tensile Strength MN/m^2	Tensile Strength (ksi)	Tensile Modulus GN/m^2	Tensile Modulus (msi)	Strain to Failure μ-m/m	Shear Strength MN/m^2	Shear Strength (ksi)
MA-1 (57.7 V/O)	297	75	Long.	1530	222	206	29.9	7100	95.2	13.8
				1630	237	199	28.9	8300	54.4	7.9
				1700	247	211	30.6	8500	77.9	11.3
				1620	235	206	29.8	8000	75.8	11.0
			Trans.	96.5	14.0	113	16.4	1900		
				86.9	12.6	133	19.3	3200		
				64.2	9.3	130	18.9	1600		
				82.7	12.0	126	18.2	2300		
	589	600	Long.	1269	184	223	32.3	6900	33.1	4.8
				1241	180	193	28.0	7300	36.5	5.3
				1255	182	208	30.2	7100	35.8	5.2
									35.1	5.1
			Trans.	33.1	4.8	82.7	12.0	1300		
				32.4	4.7	64.8	9.4	1600		
				32.8	4.8	73.8	10.7	1500		
MA-2 (46.0 V/O)	297	75	Long.	1090	158	176	25.5	6800	101	14.6
				1160	169	177	25.6	7200	91.7	13.3
				1530	221	174	25.2	8600	92.4	13.4
				1260	183	175	25.4	7500	95.2	13.8
			Trans.	97.2	14.1	112	16.3	1900		
				108	15.6	117	17.0	3200		
				128	18.5	130	18.9	7300		
				111	16.1	120	17.4	4100		
	589	600	Long.	1145	166	172	24.7	6200	29.6	4.3
				1276	185	226	32.8	6400	33.8	4.9
				1211	176	199	28.8	6300	35.8	5.2
									33.0	4.8
			Trans.	30.6	4.4	60.7	8.8	800		
				30.6	4.4	75.8	11.0	800		
				30.6	4.4	68.3	9.9	800		

nitrogen, i.e., 77K (-320F). Longitudinal and transverse tensile and shear specimens were prepared and tested at room temperature.

2.2.4 TEST RESULTS. Test results are given in Table 2-4. Heat treatment, both the solution treatment plus age (ST&A) and the solution treatment plus cryogenic soak plus age (ST&C&A), resulted in increased transverse tensile and shear strengths with little or no effect on longitudinal tensile strength properties for the unidirectional B/Al composite panels. These results were as anticipated. Also, as expected, the composite panel with the lower volume percent of boron filaments (MA-2) experienced the most improvement in properties with heat treatment.

Elastic moduli were increased about 10% for the longitudinal direction and from 0 to 10% for the transverse direction as a result of the thermal treatments. The strain-to-failure was significantly decreased with heat treatment. Heat treatment of ±45° crossplied B/Al material resulted in significant improvements (25 to 100%) for ultimate tensile strength, 0.2% yield strengths, and elastic modulus accompanied with decreases (up to 50%) in the total strain-to-failure. The greatest improvement in strength properties was obtained with the ST&C&A heat treatment.

Assuming that the reduced strain-to-failure does not become a limiting factor, it appears that improved strength and modulus properties can be achieved for either unidirectional or ±45° crossplied B/Al composite material by thermal treatment with preference for the ST&C&A condition.

2.3 MATERIAL EVALUATION

2.3.1 OBJECTIVES. The primary objective of the materials evaluation task was to determine the mechanical properties of boron/aluminum composite material to enable the establishment of minimum design values that may be used with assurance in high-integrity structures.

2.3.2 TEST MATERIALS AND PROCEDURE. It was determined that evaluation of two different layups, unidirectional and ±45°, would be necessary to meet design requirements. A minimum of 10 panels (five unidirectional and five crossplied), representing five different processing batches and three different processing times, were required for evaluation testing to develop statistical confidence in the test data. Each composite test panel was subjected to characterization testing to assure good quality test material. Characterization testing consisted of visual examination, nondestructive testing (both x-radiography and ultrasonic testing), thickness measurements, volume percent determinations, filament degradation tests, and metallographic examinations.

Results of nondestructive testing are reported and discussed in Section 2.5. Visual observations indicated good quality composite material. There were no visual surface defects nor indications of internal defects. Results of thickness measurements indicated good quality control during layup and consolidation of the composite panels.

Table 2-4. Effect of Thermal Treatments on the Room Temperature Properties of B/Al Composite Materials

Panel	Condition*	Direction	Tensile Strength MN/m^2	Tensile Strength (ksi)	Tensile Modulus GN/m^2	Tensile Modulus (msi)	Strain to Failure μ-m/m	Shear Strength MN/m^2	Shear Strength (ksi)
MA-1 (57.7 V/O)	F	Long.	1620	235	206	29.8	8000	75.8	11.0
		Trans.	82.7	12.0	126	18.2	2300		
MA-1	ST&A	Long.	1420	206	230	33.4	6600	82.7	12.0
			1690	245	234	33.9	7300	93.1	13.5
			1360	197	210	30.4	5900	129	18.7
			1490	216	225	32.6	6600	101	14.7
		Trans.	118	17.1	125	18.1	2200		
			108	15.6	137	19.8	1200		
			113	16.4	131	19.0	1700		
MA-1	ST + C+ A	Long.	1590	231	230	33.3	7300	108	15.6
			1600	232	252	36.6	7500	99.3	14.4
			1580	229	227	32.9	7100	170	24.7
			1590	231	237	34.3	7300	126	18.2
		Trans.	117	17.0	168	24.4	1100		
			106	15.4	157	22.7	1100		
			112	16.2	163	23.6	1100		
MA-2 (46.0 V/O)	F	Long.	1260	183	175	25.4	7500	95.2	13.8
		Trans.	111	16.1	120	17.4	4100		
MA-2	ST&A	Long.	1260	183	218	31.6	6400	147	21.3
			979	142	220	31.9	4900	119	17.3
			1320	191	239	34.7	6400	163	23.6
			1190	172	226	32.7	5900	143	20.7
		Trans.	190	27.6	115	16.6	2000		
			161	23.3	125	18.1	1600		
			176	25.5	120	17.4	1800		
MA-2	ST + C + A	Long.	1340	194	250	36.3	6200	164	23.8
			1200	174	203	29.4	6400	144	20.9
			1240	180	256	37.1	6300	162	23.5
			1260	183	237	34.3	6300	157	22.7
		Trans.	194	28.1	178	25.8	1300		
			219	31.7	137	19.8	2300		
			206	29.9	157	22.8	1800		

Table 2-4. Effect of Thermal Treatment on the Room Temperature Properties of B/Al Composite Material, Contd

Panel No. and Layup	Condition*	Longitudinal Tensile Strength MN/M^2	Longitudinal Tensile Strength (ksi)	Longitudinal Tensile Modulus GN/m^2	Longitudinal Tensile Modulus (msi)	Longitudinal Tensile Strain-to-Failure μm/m	Transverse Tensile Strength MN/m^2	Transverse Tensile Strength (ksi)	Transverse Tensile Modulus GN/m^2	Transverse Tensile Modulus (msi)	Transverse Tensile Strain-to-Failure μm/m	Shear Strength MN/m^2	Shear Strength (ksi)
ME-2 (Uni)	F	1448	210	200	29.0	7300	133	19.3	143	20.8	4200	170	24.7
(51.0 v/o)	ST+A	1331	193	223	32.4	6500	172	24.9	136	19.7	1300	162	23.5
		1255	182	212	30.7	6000	245	35.5	118	17.1	2300	203	29.4
		1317	191	215	31.2	6400	241	35.0	143	20.7	2300	202	29.3
		1255	182	228	33.0	5500	148	21.5	115	16.6	1900	222	32.2
		1227	178	226	32.8	6100	255	37.0	145	21.0	2300	221	32.0
		1255	182	210	30.4	5400						234	33.9
		1273	185	219	31.8	6000	212	30.8	131	19.0	2000	208	30.1
	ST+C+A	1510	219	254	36.9	6800	221	32.1	121	17.6	1500	194	28.1
		1372	199	222	32.2	6800	231	33.5	126	18.2	2200	314	45.5
		1386	201	231	33.5	6400	226	32.7	159	23.1	1500	268	38.9
		1593	231	221	32.0	7400	257	37.2	128	18.6	2200	307	44.5
		1469	213	203	29.5	6900	246	35.7	139	20.1	2000	221	32.1
		1482	215	209	30.3	7900						281	40.7
		1469	213	223	32.4	7000	236	34.2	135	19.5	1900	264	38.3

Panel No. and Layup	Condition*	Longitudinal Tensile Properties: Ultimate Strength MN/m^2	Ultimate Strength (ksi)	0.2% Yield Strength MN/m^2	0.2% Yield Strength (ksi)	Elastic Modulus GN/m^2	Elastic Modulus (msi)	Strain-to-Failure μm/m
MEX-1 (±45° Cross-plied) (47.8 v/o)	F	214	31.0	126	18.2	115	14.2	19,000

Table 2-4. Effect of Thermal Treatment on the Room Temperature Properties of B/Al Composite Material, Contd

Panel No. and Layup	Condition*	Longitudinal Tensile Properties: Ultimate Strength MN/m^2	Ultimate Strength (ksi)	0.2% Yield Strength MN/m^2	0.2% Yield Strength (ksi)	Elastic Modulus GN/m^2	Elastic Modulus (msi)	Strain-to-Failure $\mu m/m$
MEX-1	ST+A	265	38.4	227	32.9	138	20.0	8,400
		237	34.3	223	32.4	106	15.4	6,300
		262	38.0	213	30.9	177	25.7	12,900
		234	34.0	199	28.8	102	14.8	12,600
		251	36.4	228	32.3	166	24.1	9,700
		250	36.2	21.8	31.5	138	20.0	10,000
	ST+C+A	295	42.8	257	37.3	146	21.2	9,100
		278	40.3	248	35.9	182	26.4	7,500
		267	38.7	244	35.4	183	26.5	6,400
		287	41.4	248	35.9	157	22.8	8,800
		278	40.3	245	35.5	183	26.6	9,300
		281	40.7	248	36.0	170	24.7	8,200

*F = As received

ST+A = Solution treated at 799°K (980°F), 30 min., W.Q.; aged at 450°K (350°F) for 8 hours.

ST+C+A = Solution treated at 799°K (980°F), 30 min., W.Q.; soaked in LN_2 at 77°K (-320°F) for 5 min.; aged at 450°K (350°F) for 8 hours.

Volume percent determinations were made using the leaching method (i.e., a sample of B/Al was weighed, the aluminum leached away with a NaOH solution, and the dried filaments then reweighed). A knowledge of the density of the filaments and matrix material then enabled the calculation of volume percent of filaments present in the composite. Volume percentages ranged from 48.7 to 51.2 for the unidirectional panels (ME-1 through ME-5) and from 47.7 to 50.1 for the ±45° crossplied panels (MEX-1 through MEX-5). Individual values are reported in Section 2.3.3 with the mechanical property test results. Results of metallographic examinations indicated good quality, mostly well bonded composite test material. Typical photomicrographs are shown in Figure 2-4.

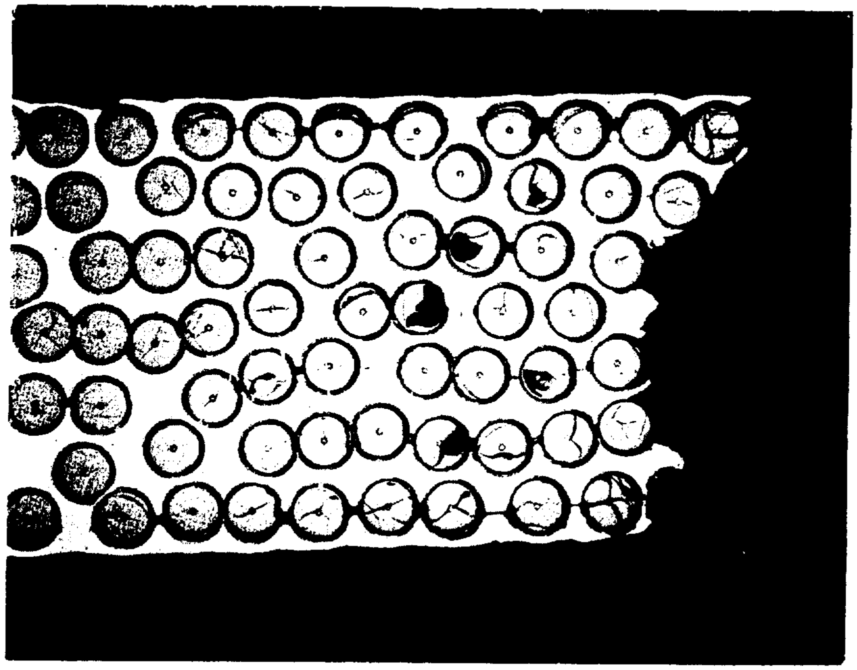
Upon completion of characterization testing, specimen blanks for tensile, compression, shear, and notched tensile specimens were laid out, identified, and machined from the composite test panels. Specimen configurations and sizes are shown in Figure 2-3. Each specimen was identified, individually measured, and checked for quality, surface condition, and dimensional accuracy in preparation for testing.

A total of 432 specimen tests consisting of tensile, compression, shear and notched tensile tests were performed at room temperature, 77K, 475K, 589K, and 700K (-320F, 400F, 600F, and 800F), as shown in Table 2-5. Stress/strain curves were obtained by strain gages and/or extensometers on all tensile and compression tests.

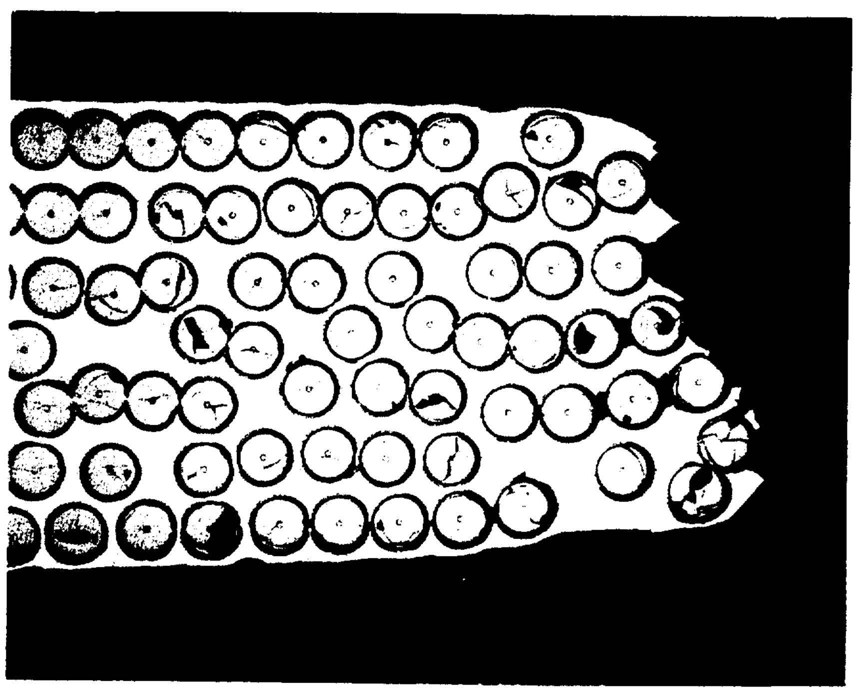
Table 2-5. Material Evaluation Test Specimens

			Minimum Number of Specimens* Tested At					
Layup	Test	Dir.	RT	77K (320F)	475K (400F)	589K (600F)	700K (800F)	Total
Unidirectional	Tensile	Long.	30	6	6	6	6	54
	Tensile	Trans.	30	6	6	6	6	54
	Compression	Long.	30	6	6	6	6	54
	Compression	Trans.	30	6	6	6	6	54
	Shear (Double)		30	6	6	6	6	54
	Notched Tensile	Long.	30	6	6	6	6	54
± 45°	Tensile		30	6	6	6	6	54
	Compression		30	6	6	6	6	54
	Total		240	48	48	48	48	432

*Test specimens taken from 10 different composite panels representing 5 different processing batches and 3 different times (1, 2, and 3 months after contract go-ahead). Six replicate specimens tested per panel (for a total of 30 tests per property) at room temperature. One composite panel, 6 replicate tests, tested at elevated and cryogenic temperatures. Strain gages (on a minimum of two specimens per condition) and extensometers used for determination of modulus and Poisson's ratio on tensile and compression tests.

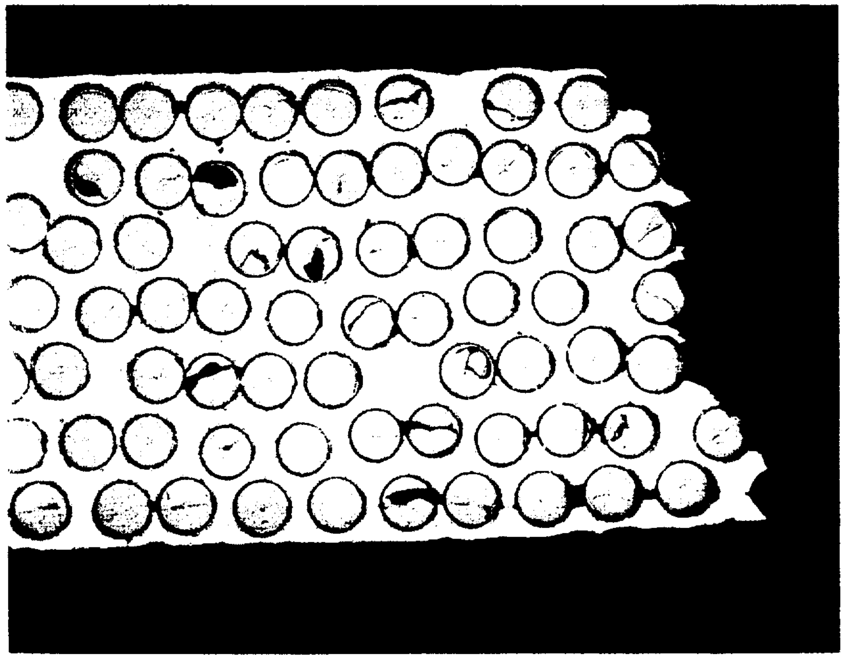


ME-1 Unidirectional Panel (D1439)   50X

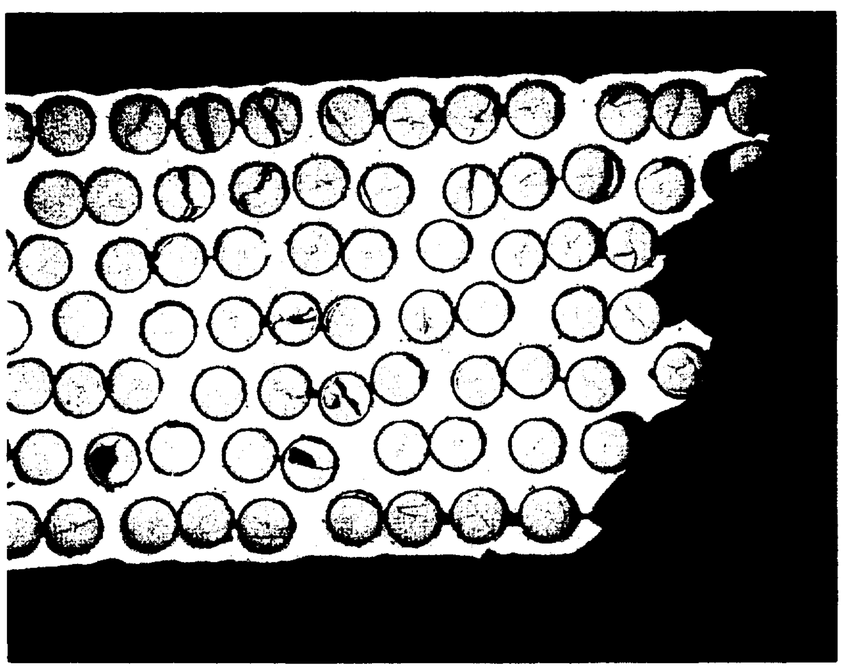


ME-2 Unidirectional Panel (D1440)   50X

Figure 2-4. Photomicrographs of B/Al Composite Test Panels Showing Typical Microstructure and Transverse Tensile Failures

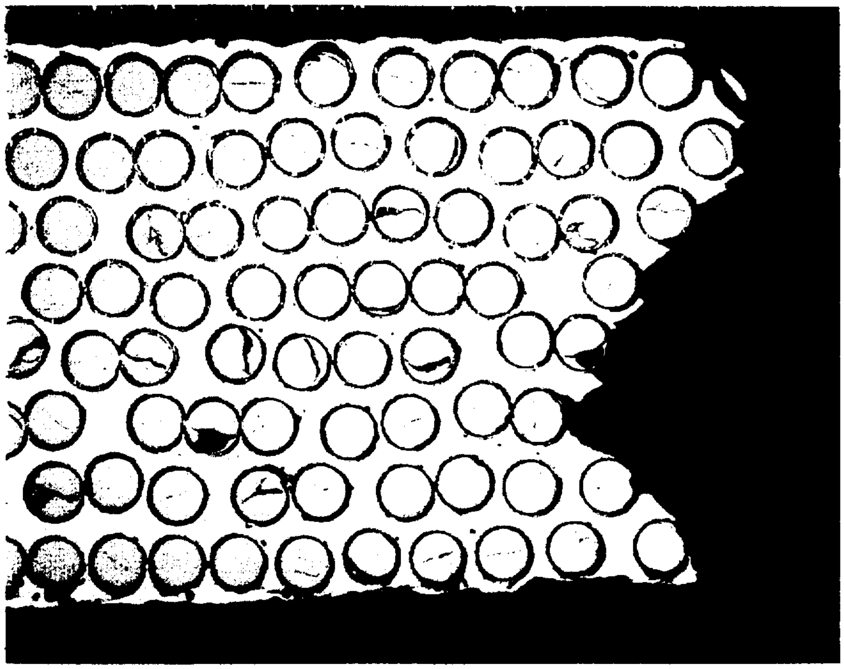


ME-3 Unidirectional Panel (D1441)   50X

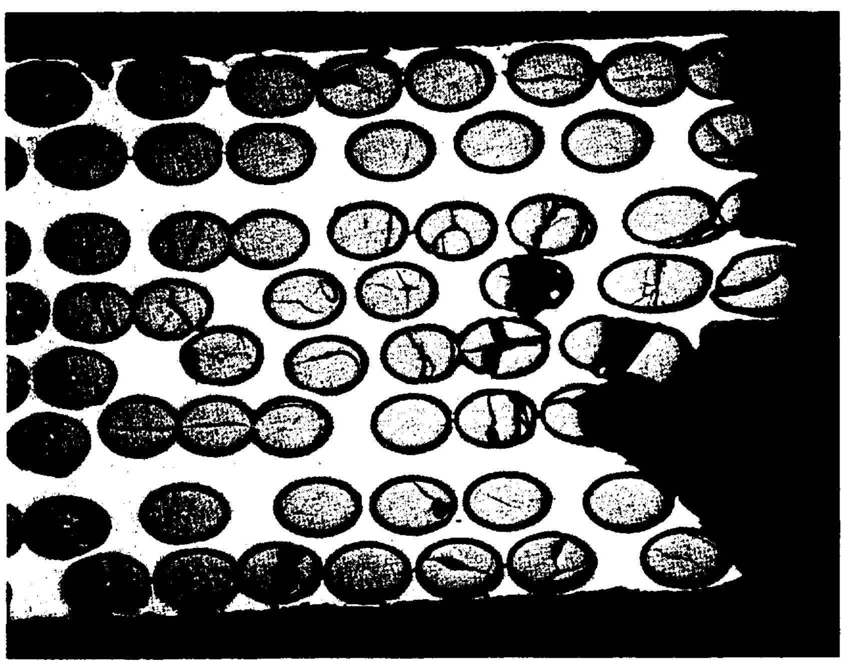


ME-4 Unidirectional Panel (D1442)   50X

Figure 2-4. Photomicrographs of B/Al Composite Test Panels Showing Typical Microstructure and Transverse Tensile Failures (Continued)



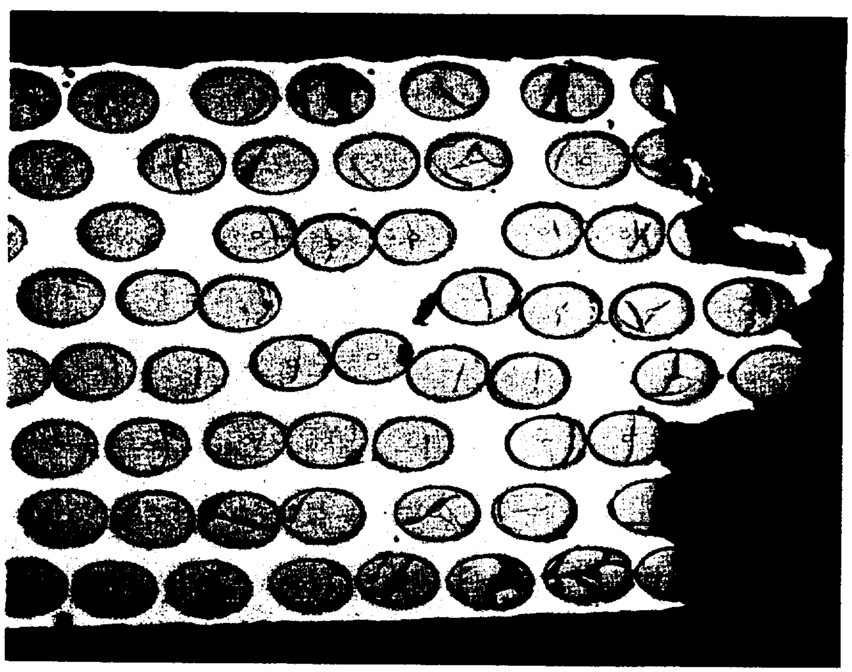
ME-5 Unidirectional Panel (D1443) 50X



MEX-1 ±45° Crossplied Panel (D1444) 50X

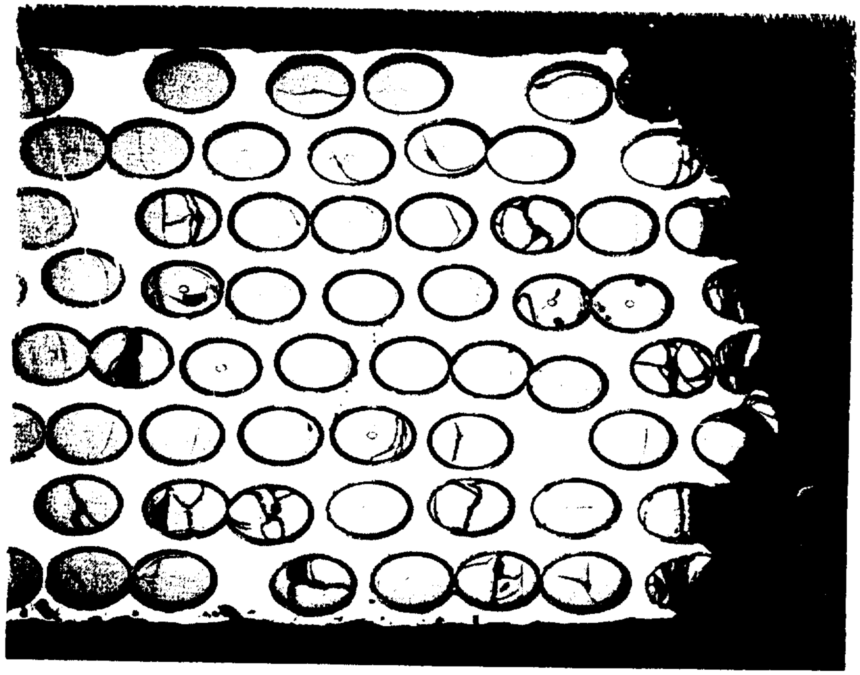
Figure 2-4. Photomicrographs of B/Al Composite Test Panels Showing Typical Microstructure and Transverse Tensile Failures (Continued)

MEX-2 ±45° Crossplied Panel (D1445) 50X

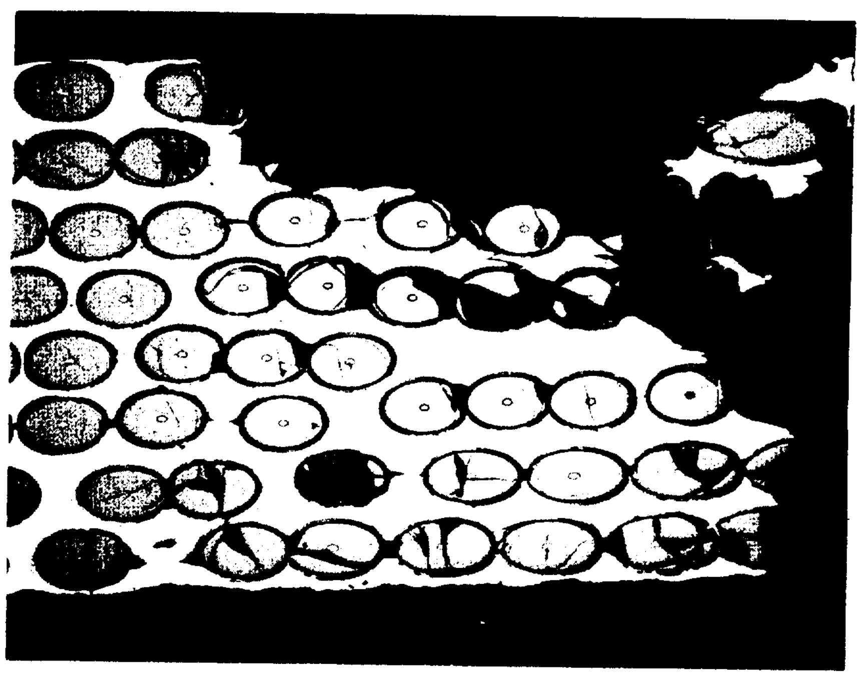


MEX-3 ±45° Crossplied Panel (D1446) 50X

Figure 2-4. Photomicrographs of B/Al Composite Test Panels Showing Typical Microstructure and Transverse Tensile Failures (Continued)



MXE-4 ±45° Crossplied Panel (D1447) 50X



MXE-5 ±45° Crossplied Panel (D1448) 50X

Figure 2-4. Photomicrographs of B/Al Composite Test Panels Showing Typical Microstructure and Transverse Tensile Failures (Continued)

2.3.3 TEST RESULTS AND DISCUSSION. Actual test results of mechanical property testing are given in Tables B-1 and B-2 and are summarized in Table 2-6 for the unidirectional B/Al material and in Table 2-7 for the ±45° crossplied B/Al composite material. Graphical presentations of the test data are given in Figures 2-5 through 2-8 for unidirectional material and in Figures 2-9 and 2-10 for the crossplied material.

The unidirectional B/Al composite material exhibited exceptionally high longitudinal and transverse tensile strength properties as may be seen in Table 2-6 and Figures 2-5 and 2-6. Room temperature strength properties average 1289 MN/m^2 (216 ksi) for the longitudinal direction and 133 MN/m^2 (19.3 ksi) for the transverse direction. The tensile modulus averaged 214 GN/m^2 (31.1 msi) for the longitudinal and 136 GN/m^2 (19.7 msi) for the transverse direction. Poisson's ratio data obtained from strain-gaged specimens indicate averages of 0.23 and 0.12, respectively, for the longitudinal and transverse directions. Room-temperature shear strengths average 157 MN/m^2 (22.6 ksi). Tensile and shear tests at cryogenic temperatures, 77K(-320F), indicated little or no change for longitudinal tensile and shear properties from those obtained at room temperature. However, significant increases in transverse tensile strength (about 25%) and modulus (about 12%) were noted at the lower test temperatures. These results were anticipated due to the higher strength of the aluminum-matrix material at low temperatures. Also, as expected, elevated temperatures resulted in a decrease in tensile and shear properties particularly at 589K (600F) and at 700K (800F) as shown in Figures 2-5 and 2-6.

As can be seen from Table 2-6 and Figures 2-7 and 2-8, unidirectional B/Al composite material possesses exceptionally high compressive strength properties. Averages are 1951 MN/m^2 (283 ksi) for the longitudinal direction and 285 MN/m^2 (41.3 ksi) for the transverse direction. Room temperature compression strengths are about double tensile strength properties for unidirectional B/Al in the transverse direction. For the longitudinal direction, compression strengths are about 35% greater than average tensile strength properties. In general, the compressive strength and modulus properties increased at cryogenic temperatures and decreased at elevated temperatures, particularly for the transverse direction.

As shown in Table 2-6, the notched tensile strength of B/Al composite material averages 1006 MN/m^2 (146 ksi) at room temperature and decreases to an average of 752 MN/m^2 (109 ksi) at 77K (-320F), but increase at elevated temperatures to 1192 MN/m^2 (173 ksi) at 477K (400F), 1158 MN/m^2 (168 ksi) at 589K (600F) and 1076 MN/m^2 (156 ksi) at 700K (800F). The notched/unnotched tensile strength ratio for B/Al is 0.68 at room temperature. This ratio is in good agreement with previous results obtained on diffusion-bonded B/Al (4.0 mil boron) composite sheet material (Reference 10). The notched/unnotched tensile strength ratio declines to 0.50 at liquid nitrogen temperatures and increases to 0.82 at 477K (400F). This result indicates that B/Al composite sheet material is more notch-sensitive at cryogenic temperatures, but less notch-sensitive at elevated temperatures than it is at room temperature.

Table 2-6. Summary of Mechanical Properties of Unidirectional B/Al Composite Material

Test Temp K	(F)	Direction	Tensile Strength MN/m²	(ksi)	Tensile Modulus GN/m²	(msi)	Strain to Failure μ m/m	Poisson's Ratio	Shear Strength MN/m²	(ksi)	Compression Strength MN/m²	(ksi)	Compression Modulus GN/m²	(msi)	Poisson's Ratio	Notched Tensile Strength MN/m²	(ksi)	Notched/Unnotched Tensile Strength Ratio
297	(75)	Long	1488	(216)	215	(31.1)	7200	0.23	155	(22.6)	1948	(283)	257	(37.3)		1006	(146)	0.68
		Trans	133	(19.3)	136	(19.7)	5700	0.12	—	—	285	(41.3)	162	(23.5)	0.12	—	—	—
77	(-320)	Long	1499	(218)	209	(30.4)	7500	0.27	162	(23.5)	1871	(271)	266	(38.5)		752	(109)	0.50
		Trans	179	(25.9)	155	(22.5)	2900	0.12	—	—	421	(61.1)	155	(22.5)	0.13	—	—	—
477	(400)	Long	1461	(212)	206	(29.9)	7300	0.20	97	(14.1)	1594	(231)	220	(31.9)	—	1192	(173)	0.82
		Trans	122	(17.7)	96	(13.8)	2200	0.08	—	—	206	(29.8)	164	(23.8)	—	—	—	—
589	(600)	Long	1332	(193)	199	(28.9)	6200	0.13	59	(8.5)	1104	(160)	172	(25.0)	—	1156	(168)	0.87
		Trans	62	(9.0)	73	(10.6)	—	—	—	—	104	(15.1)	99	(14.4)	—	—	—	—
700	(800)	Long	1178	(171)	191	(27.7)	—	0.16	37	(5.3)	597	(86.9)	145	(21.0)	—	1073	(156)	0.91
		Trans	31	(4.5)	62	(9.0)	—	—	—	—	55	(8.1)	86	(12.4)	—	—	—	—

Table 2-7. Summary of Mechanical Properties of ±45° Crossplied B/Al Composite Material

Test Temp K	F	Tensile Strength MN/m²	(ksi)	0.2% Yield Strength MN/m²	(ksi)	Tensile Modulus GN/m²	(msi)	Strain to Failure μ m/m	Poisson's Ratio	Compression Strength MN/m²	(ksi)	Compression Modulus GN/m²	(msi)	Poisson's Ratio
297	(75)	249	(36.2)	118	(17.1)	117	(16.9)	24,600	0.48	502	(73.0)	139	(20.1)	0.29
77	(-320)	227	(32.9)	137	(19.8)	116	(16.7)	12,200	0.38	611	(88.7)	142	(20.6)	—
477	(400)	240	(34.8)	156	(22.6)	110	(16.0)	52,800	0.56	453	(65.8)	130	(18.7)	—
589	(600)	133	(19.3)	69	(10.1)	73	(10.6)	61,300	0.80	217	(31.5)	99	(14.3)	—
700	(800)	93	(13.5)	36	(5.2)	66	(9.6)	71,000	—	106	(15.4)	86	(12.4)	—

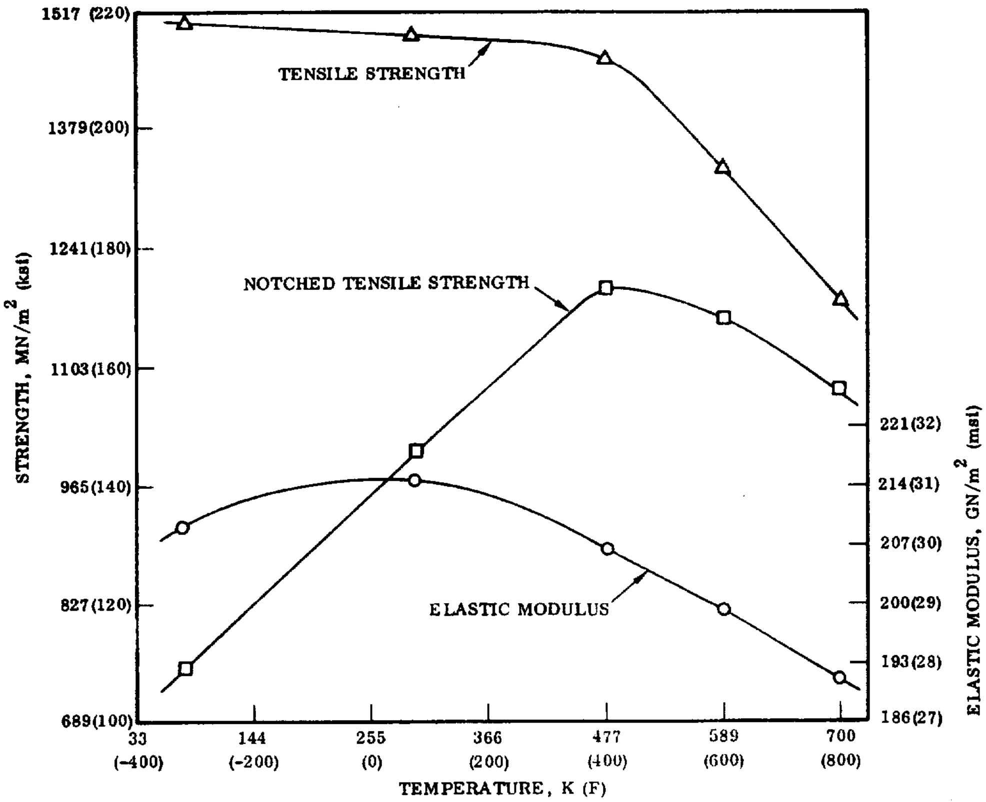


Figure 2-5. Longitudinal Tensile Properties of Unidirectional B/Al as a Function of Test Temperature

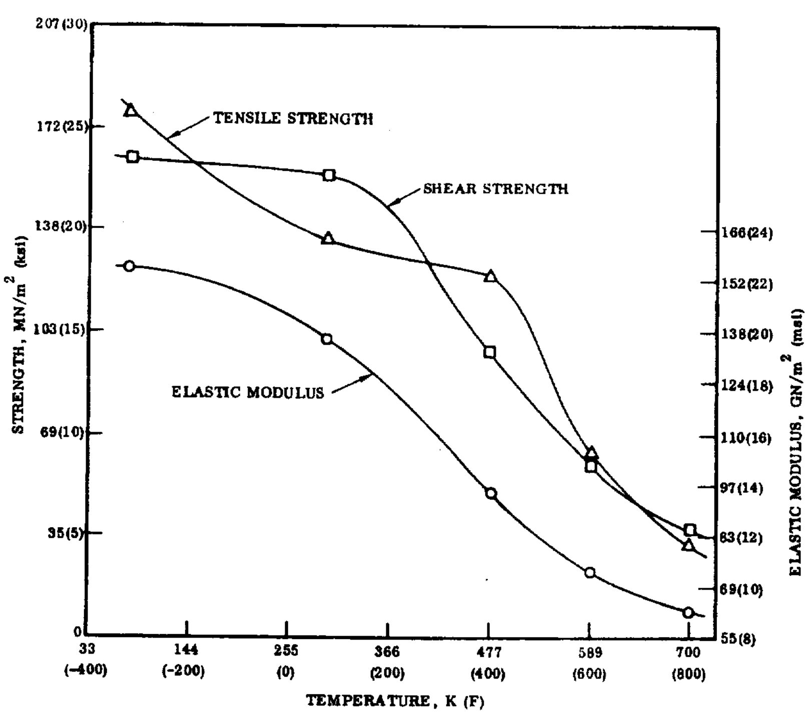


Figure 2-6. Transverse Tensile Properties and Shear Strength of Unidirectional B/Al as a Function of Test Temperature

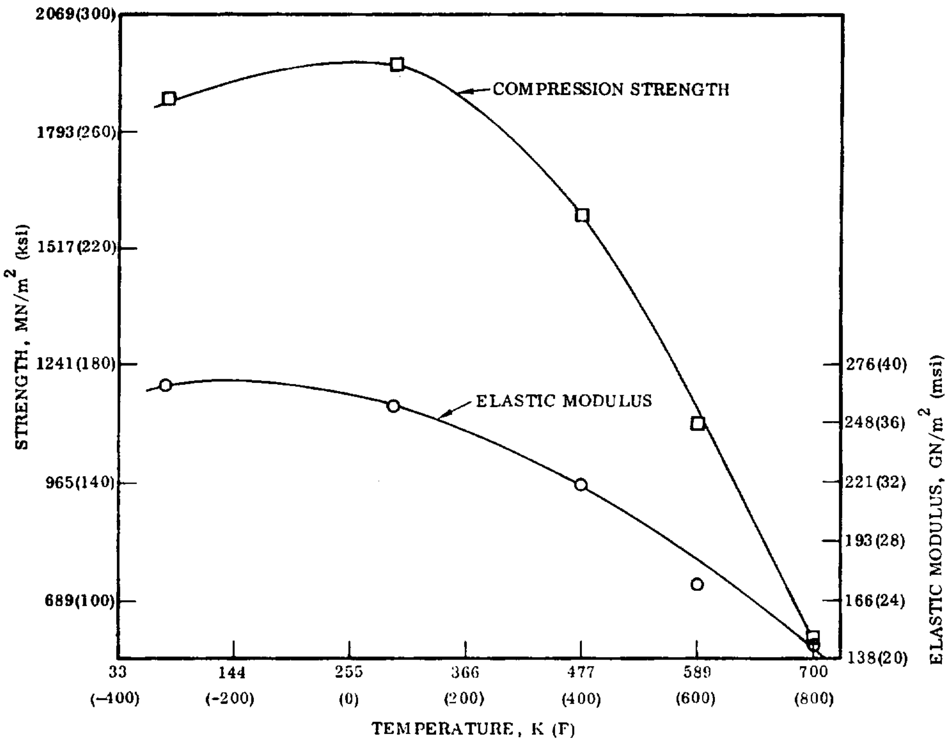


Figure 2-7. Longitudinal Compression Properties of Unidirectional B/Al as a Function of Test Temperature

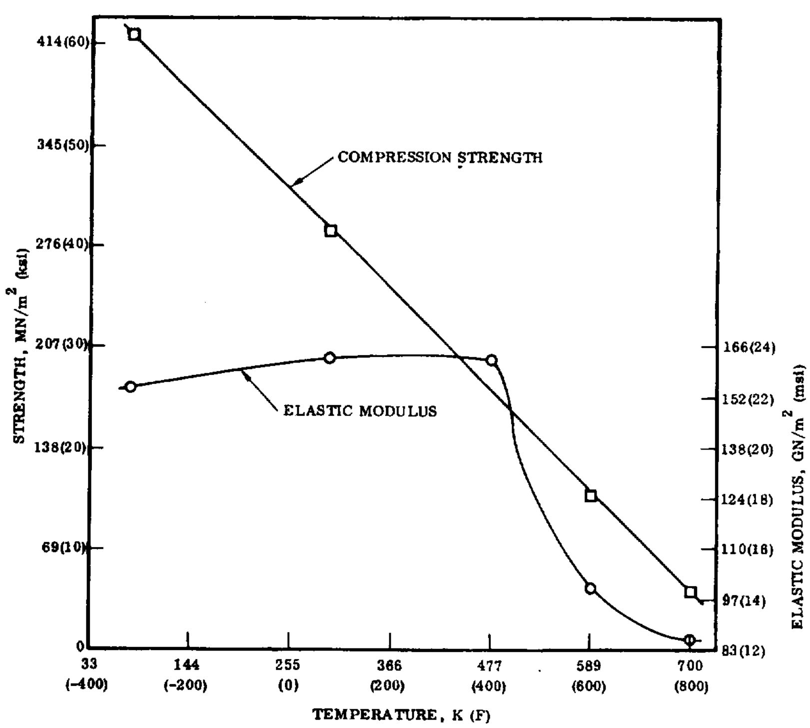


Figure 2-8. Transverse Compression Properties of Unidirectional B/Al as a Function of Test Temperature

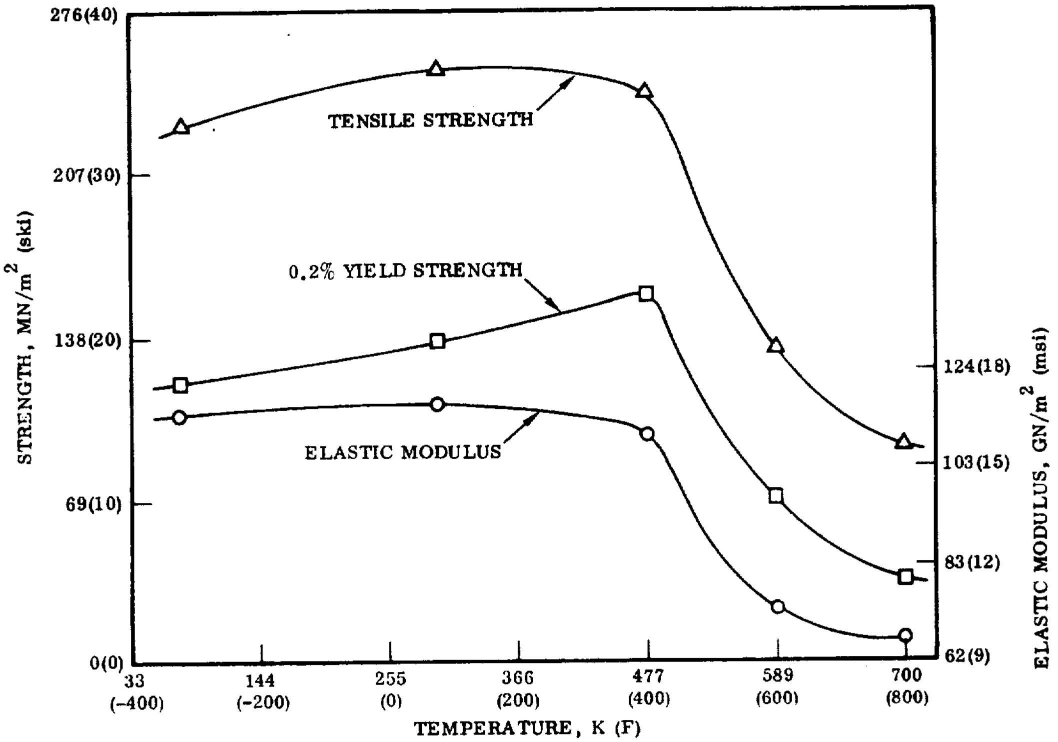


Figure 2-9. Tensile Properties of ±45° Crossplied B/Al as a Function of Test Temperature

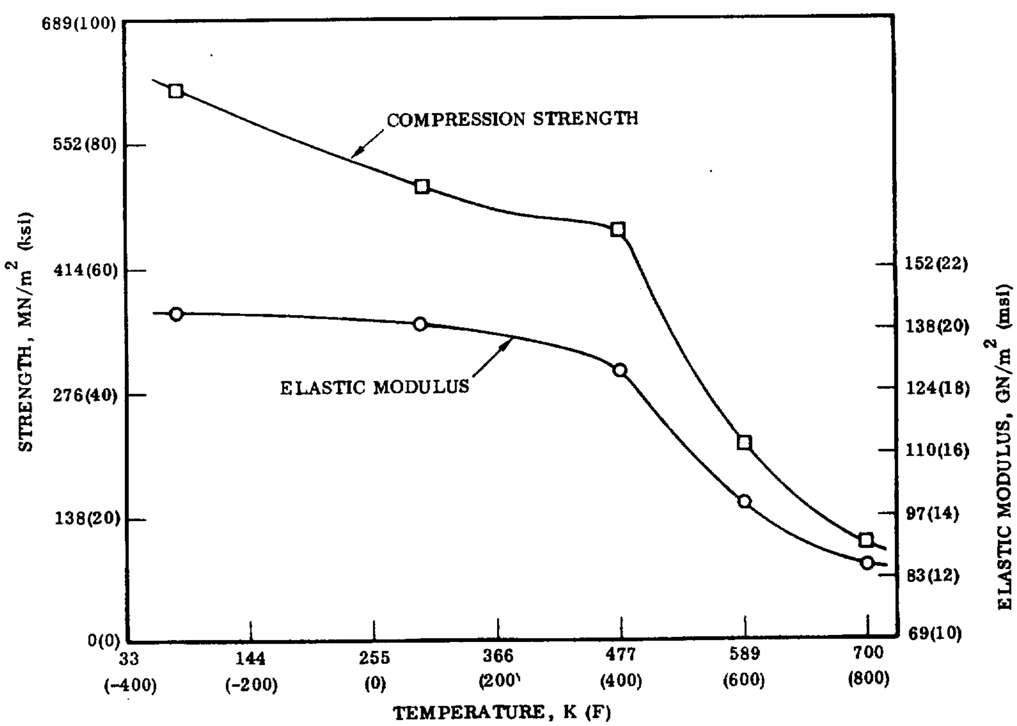


Figure 2-10. Compression Properties of ±45° Crossplied B/Al as a Function of Test Temperature

The mechanical properties of ±45° crossplied B/Al composites are presented in Table 2-7 and Figures 2-9 and 2-10. Included are tensile and compressive properties at room, cryogenic, and elevated temperatures. The average room-temperature tensile strength of ±45° crossplied B/Al composite material is 248 MN/m^2 (36.2 ksi) with an average modulus of 117 GN/m^2 (16.9 msi) and average Poisson's ratio of 0.48. There was little or no change in tensile strength and modulus properties at 77K (-320F) or at 477K (400F); however, a significant decrease in properties was obtained at 589K (600F) and at 700K (800F). A very large strain-to-failure was obtained at all test temperatures.

Also, as can be seen in Table 2-7 and Figure 2-6, compression strengths of ±45° crossplied B/Al are considerably higher than tensile strength properties. An overall average of 503 MN/m^2 (73.0 ksi) compressive strength was obtained at room temperature. Compressive modulus averaged 139 GN/m^2 (20.1 msi) and Poisson's ratio averaged 0.29 at room temperature. Compressive strength and modulus properties increased at cryogenic temperatures and decreased at elevated temperatures, as expected for the ±45° crossplied B/Al composite material.

2.3.4 STATISTICAL ALLOWABLES. The test data reported in Tables B-1 and B-2 were statistically analyzed to determine room-temperature design failure loads. The results are summarized in Table 2-8. Using the curves of Figure 2-11, the probability levels for design allowables can be selected by the choice of the standard deviation correction factor.

Table 2-8. Room Temperature Mean and Standard Deviation Statistical Evaluation of Failure Load

	Unidirectional (UD) Composite					Crossplied Composite	
	Tension		Compression		Shear	±45°	
*	L	T	L	T		T	C
S	18.949	3.026	41.485	3.239	6.116	4.869	12.913
$\bar{X}$	215.8	19.25	282.14	41.32	22.52	36.13	72.97
n	30	29	28	30	30	30	30

*S = standard deviation $= \sqrt{\dfrac{\Sigma_i^n (X_i - \bar{X})^2}{n-1}}$

$\bar{X}$ = mean value $= \dfrac{\Sigma_i^n X_i}{n}$

n = number of samples

Note: For clarity, only English units are shown.

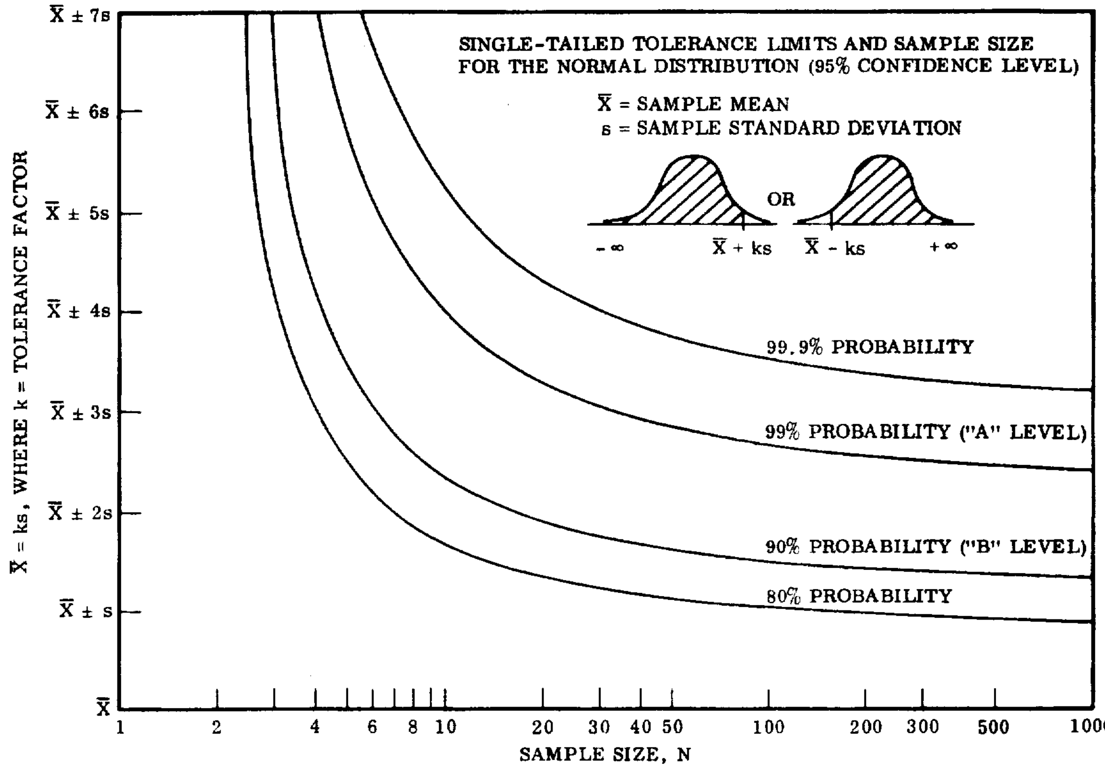


Figure 2-11. Sigma, Sample Standard Deviation, and Probability Levels

2.4 ENVIRONMENTAL PROTECTION

The objective of the environmental protection study was to determine the susceptibility of B/Al composite material to corrosion and to evaluate corrosion protection systems to be used on test components and applicable full-size Space Shuttle hardware. Two environments for Space Shuttle structure were included in this study: one, a low-temperature environment where temperatures of 77K to 366K (-320F to 200F) are experienced, and the other, a high-temperature environment, ambient up to 589K (600F). Both environments included the effects of warm, humid seacoast exposure. All surface treatments and coating systems had to be compatible with proposed assembly procedures.

In previous work (References 1 through 4 and 7), it has been found that B/Al composite materials are somewhat more susceptible to corrosion than aluminum structures, especially at edges where both boron and aluminum are exposed to the corrosive environment. In these same studies, effective corrosion resistance was achieved by a paint finish system applied over a chemical film treatment. Additional edge and fastener protection could be provided by sealants. This program extended these studies to a wider range of temperature exposure and application to larger size structural components.

2.4.1 INITIAL SCREENING. An initial screening program was conducted to determine which coating systems should be used for final evaluations. Coating systems, an acrylic, a polyurethane, and an epoxy, suitable for the low-temperature range, 77K to 366K (-320F to 200F), were applied and evaluated on small test coupons. The coupons were unidirectional B/Al composite material approximately 1.3 by 5 by 0.11 cm (0.5 by 2 by 0.05 inches); these were broken sections of tested shear specimens. These coupons were scribed after coating and evaluated by visual inspection after alternate salt spray, 366K (200F) oven, and liquid nitrogen exposures.

After an exposure of two hours at 366K (200F), one hour in liquid nitrogen, and 168 hours of salt spray, all three of the coating systems appeared to be performing well. The control specimen of unprotected B/Al composite was severely corroded. A specimen with alodine 1200 surface treatment resisted corrosion much better than the bare material, but corrosion had begun along edges where both aluminum and boron were exposed. These specimens are shown in Figure 2-12.

Similarily, coatings for high-temperature service, ambient to 589K (600F), a polyimide, a silicone, and a fluorocarbon, were evaluated on small test coupons. These coupons were scribed and evaluated by visual inspection after alternate salt spray and 589K (600F) oven exposure.

After an exposure of two hours at 589K (600F) and 168 hours of salt spray, only the polyimide and the flurocarbon coating offered adequate corrosion protection. The silicone coating was brittle and appeared to accelerate corrosion compared to the bare B/Al composite control specimen. Chromic acid anodize also offered good corrosion resistance without any other protective coating. During the 589K (600F) portion of the exposure, the fluorocarbon coating softened and portions of the scribe marks were "healed." The softened coating also bonded to the handling tray where they were placed for this exposure. They had to be pryed loose after cooling. The high-temperature corrosion protection test panels after exposure are shown in Figure 2-13.

2.4.2 SPECIMEN EXPOSURE. From the results of the screening tests, two low-temperature-resisting coating systems — a polyurethane and an acrylic were selected for further evaluations. The coating systems consisted of an application of a chemical conversion coating and a chromate inhibited epoxy polyimide primer followed by the two topcoat materials, the polyurethane and the acrylic lacquer. Three high-temperature-resisting corrosion-protection systems — a polyimide, a silicone (one not included in the initial screening tests), and chromic acid anodize — were selected for further evaluations. Each of these corrosion-protection systems was applied to two sets of triplicate transverse tensile test specimens.

One set of specimens of each coating and controls was exposed to a temperature exposure cycle followed by three-month seashore exposure at the Point Loma Coast Guard Lighthouse. The temperature exposure cycle for the high-temperature resisting coatings consisted of heating to 589K (600F) for two hours followed by air cooling to

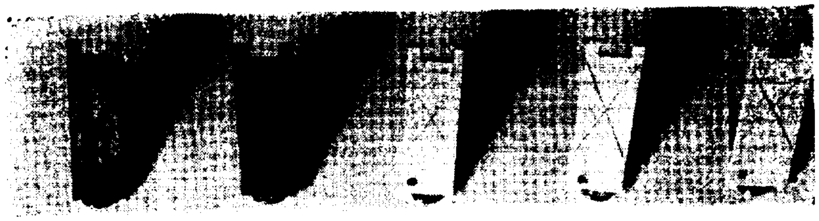


Figure 2-12. Corrosion Prevention Coating Specimens, Low-Temperature Resisting, After Two Hours at 366K (200F), One Hour in Liquid Nitrogen, and 168 Hours in Salt Spray (118296B)

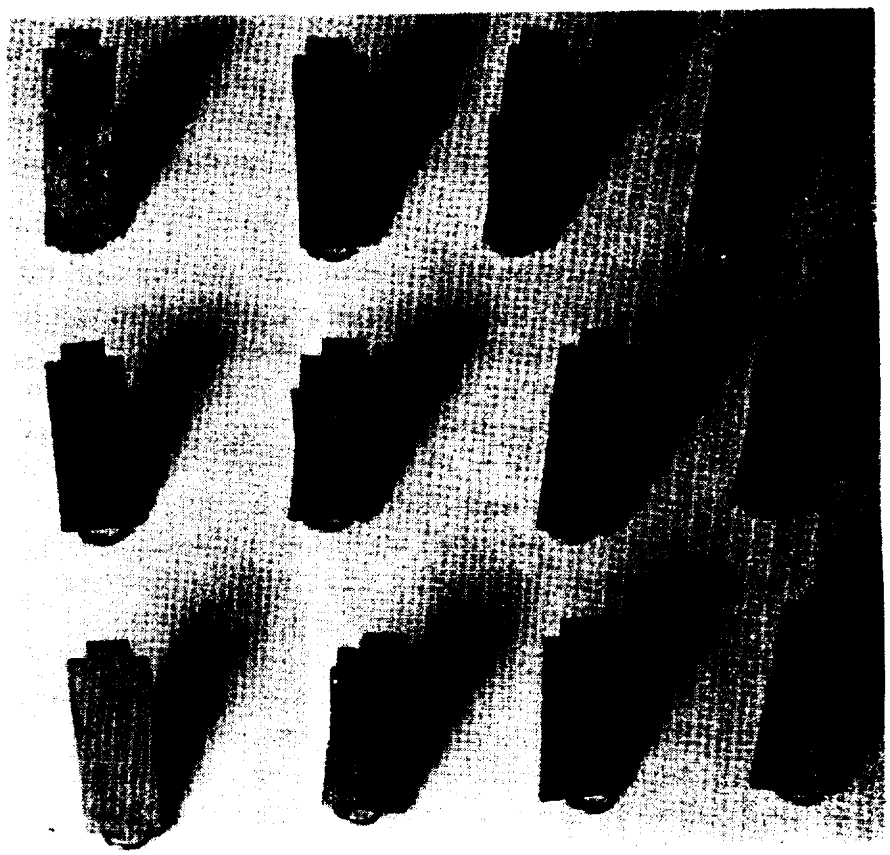


Figure 2-13. Corrosion Prevention Coating Specimens, High-Temperature Resisting, After Two Hours at 589K (600F) and 168 Hours in Salt Spray (118297B)

ambient. For the low-temperature-resistant coatings, the temperature cycle consisted of cooling to 77K (-320F) for two hours followed by heating to 366K (200F) for two hours.

The other set of specimens of each coating and controls was subjected to accelerated weathering in 5% salt spray and to thermal cycling. Total salt-spray exposure was 500 hours, and 18 thermal cycles were completed. Thermal cycling for the low-temperature-resisting coating systems consisted of 15 minutes of immersion in liquid nitrogen [77K (-320F)] followed by 45 minutes exposure at 366K (200F) in an air-circulating oven. The thermal cycle for the high-temperature-resisting systems consisted of heating to 589 (600F) for 45 minutes in an air-circulating oven followed by air cooling to room temperature [297K (75)].

2.4.3 RESULTS. After 500 hours of salt spray exposure, specimens coated with the low-temperature-resisting, corrosion-protection systems appeared to be unaffected by the accelerated corrosion and cyclic temperature testing. Both the polyurethane and acrylic coating systems performed well under these test conditions. Control test specimens without a corrosion-protective coating were moderaly corroded during the exposure. Two of the three specimens of each set are shown in Figure 2-14. One specimen of each set has been tipped up so the edge is visible.

Specimens coated with the polyurethane and acrylic exposed for three months at the seashore appeared to be effectively resisting corrosion. The uncoated control specimens were moderately corroded. Corrosion products appeared as a lighter color than those appearing on the specimens exposed to the salt spray. These specimens, one of each set tipped for viewing the edge, are shown in Figure 2-15.

The high-temperature-resisting, corrosion-protection systems were not as effective at preventing corrosion under the test conditions. After 350 hours of salt spray exposure, the silicone-coated specimens were more severely corroded than the uncoated control specimens and were eliminated from further testing. The silicone-coated speciments exposed at the seashore were also corroded more severely than the control specimens. It appears that corrosion, possibly filiform corrosion, was initiated on the polyimide-coated specimens exposed to salt spray for 500 hours. The polyimide coating was blistered in many areas of the surface, and mild surface corrosion is evident. However, the edges appear to be effectively protected. There was less evidence of film damage and corrosion on the polyimide-coated specimens exposed at the seashore. Specimens that were chromic acid anodized appeared to resist corrosion quite well in both the salt spray and seashore exposures. Only a few spots appear to have been lightly corroded. Specimens exposed to salt spray are shown in Figure 2-16 and those exposed at the seashore are shown in Figure 2-17. The damage to the lower portion of the chromic acid anodize specimens (Figure 2-17) was a result of poor specimen quality and the anodizing process, not corrosive attack.

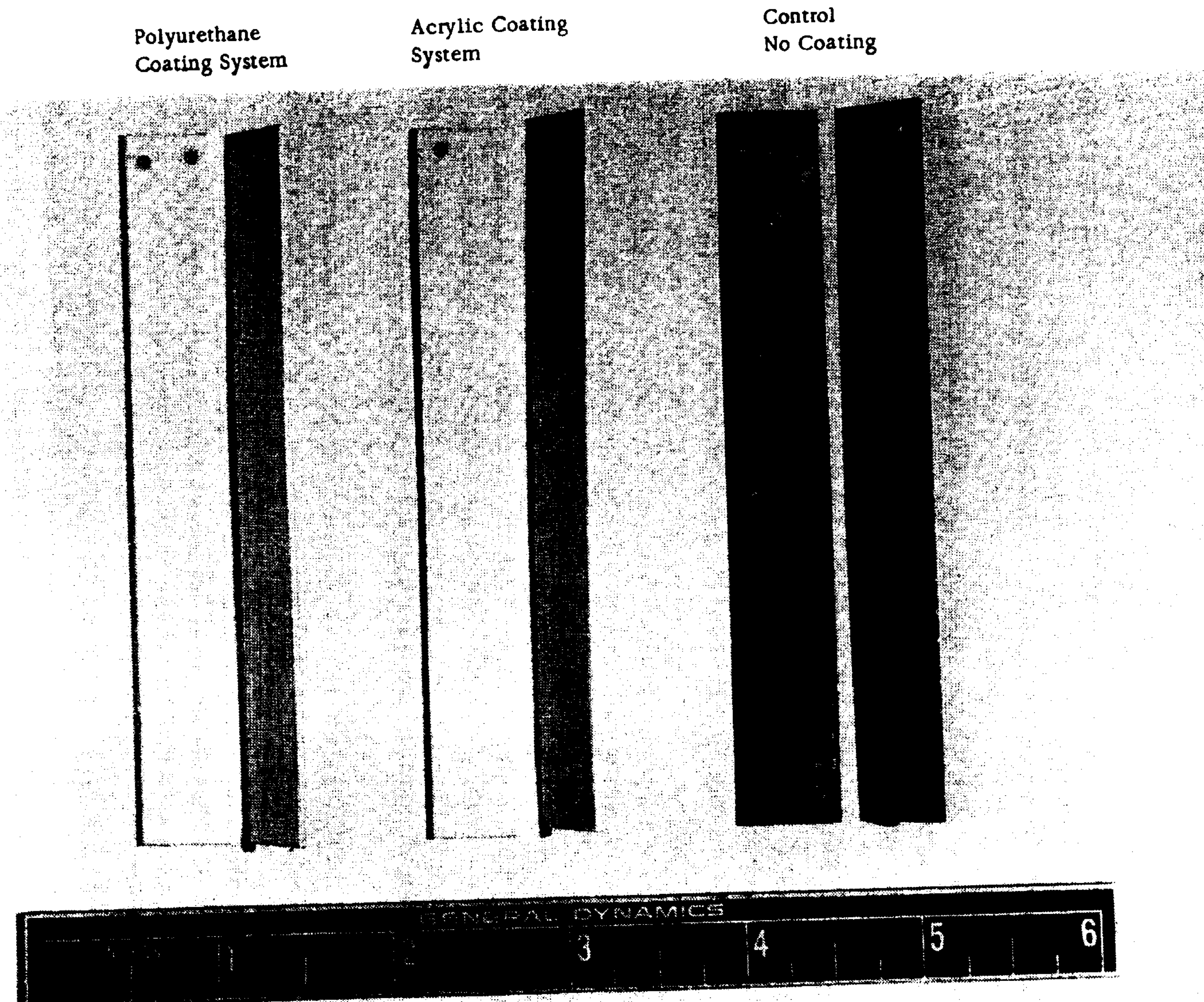


Figure 2-14. Corrosion-Prevention-Coating Specimens, Low-Temperature Resisting, After 500 Hours of Salt Spray and 18 Thermal Cycles (122809B)

Control
No Coating

Acrylic Coating
System

Polyurethane
Coating System

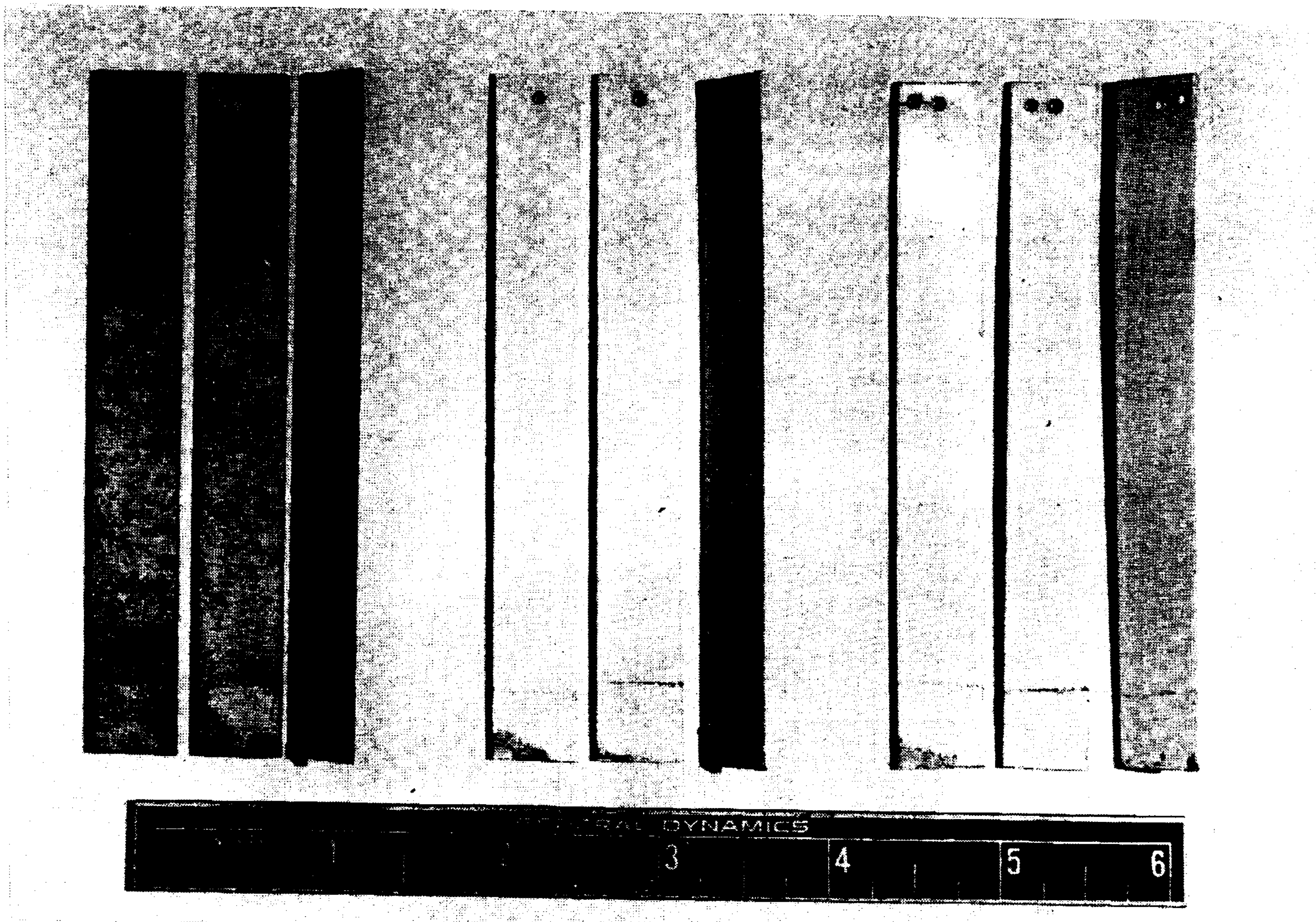


Figure 2-15. Corrosion-Prevention-Coating Specimens, Low-Temperature Resisting, After Three Months Seashore, Two Hours at 77K(-320F), and Two Hours at 366K(200F) Exposure (122811B)

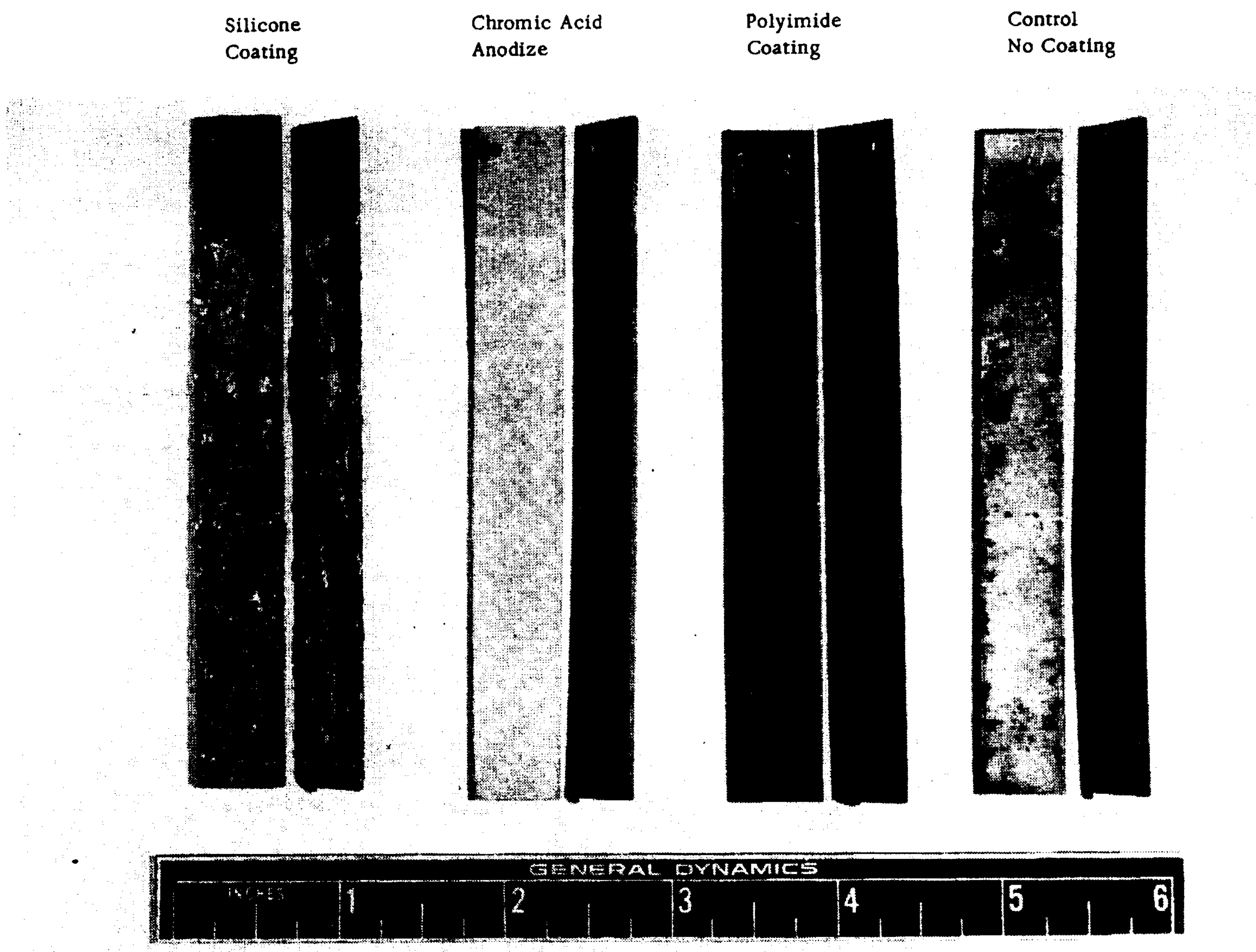


Figure 2-16. Corrosion-Prevention-Coating Specimens, High-Temperature Resisting, After 500 Hours of Salt Spray and 18 Thermal Cycles (122810B)

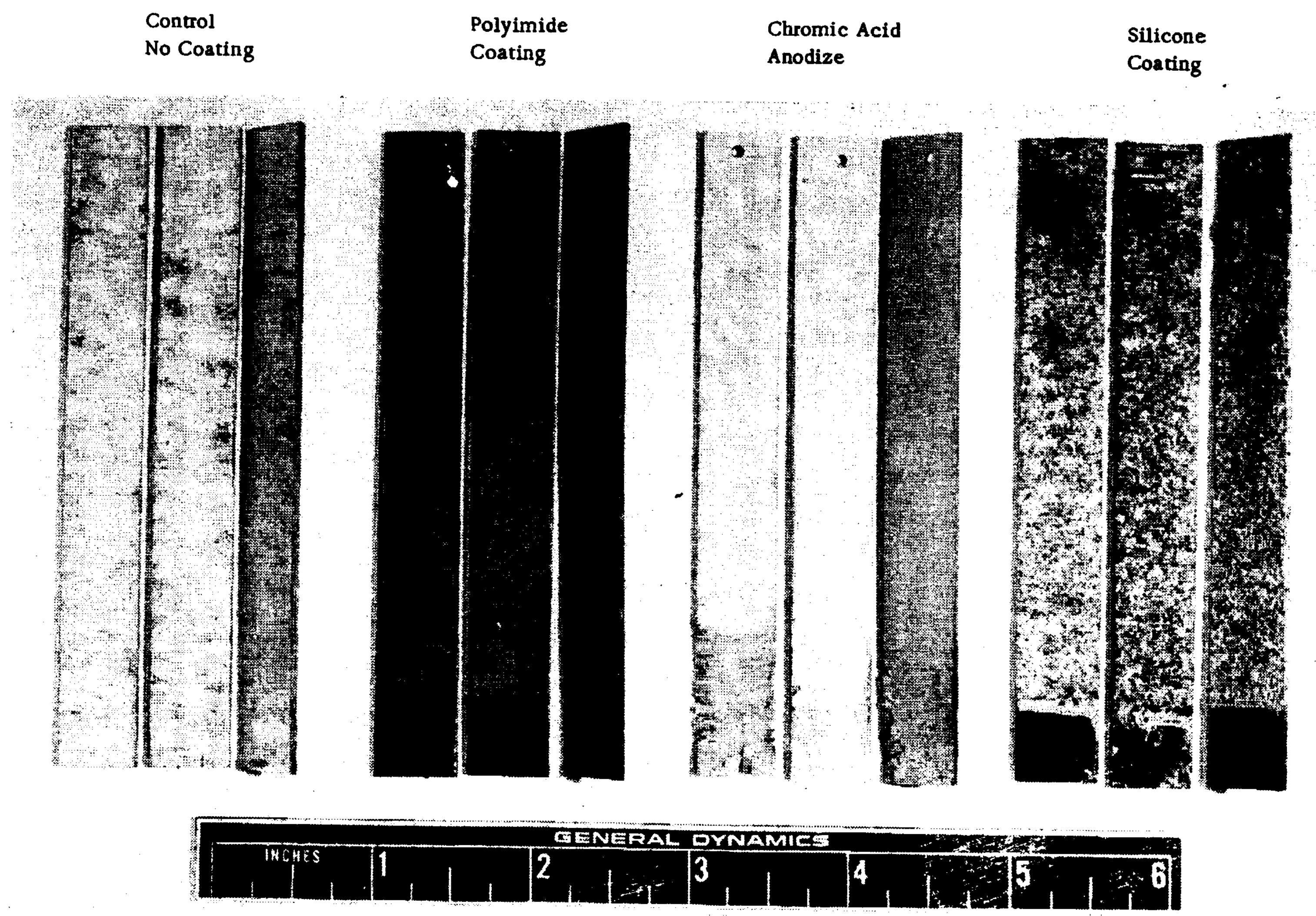


Figure 2-17. Corrosion-Prevention-Coating Specimens, High-Temperature Resisting, After Three Months Seashore and Two Hours 589K(600F) Exposure (122808B)

Transverse tensile specimens used to evaluate the various corrosion protection systems were tested to determine any change in mechanical properties that may have occurred. Test results are tabulated in Table 2-9. Analysis of the data indicates that the acrylic and polyurethane coating systems were effective in preventing corrosion when subjected to 500 hours of salt spray of three months of seashore exposure. Because of the scatter in results and the small number of samples, a loss in tensile strength of less than about 10% cannot be considered significant.

The high-temperature-resisting, corrosion-protection systems appear to be less effective. The silicone coating accelerated corrosion and severe degradation of tensile strength resulted. From the visual appearances of the specimens, the polyimide coating appeared more effective than the tensile strength loss would indicate. However, corrosion of the aluminum took place under the polyimide coating, which resulted in a loss in transverse tensile strength compared to the uncoated control specimens. The anodized specimens also appeared to have little or no corrosion, yet the loss in tensile strength was considerable. A specimen, similar to the test specimens, was prepared with the anodizing process and tested without being subjected to either temperature cycling or a salt environment. This specimen exhibited a strength decrease equivalent to those of the environmental test specimens. Close examination revealed that dissolution of fibers along the edges of the specimens had occurred, which produced a notched effect in the specimen that resulted in a decrease in specimen tensile strength.

This result was verified when a ±45° crossply specimen was anodized and did not exhibit any strength degradation; this was expected because the crossply material is not as notch sensitive as unidirectional material. It therefore appears that anodizing can be used for high-temperature environmental protection either on crossplied material or unidirectional material of substantial size where the small dissolution of fibers would not seriously degrade tensile strength.

2.4.4 DISCUSSION. These tests indicate that environmental protection of B/Al composites in low-temperature environments may be achieved with either the polyurethane or the acrylic coating systems. These systems are compatible with standard composite manufacturing processes.

Achieving effective environmental protection for high-temperature applications appears more difficult. Chromic acid anodizing was the most effective system examined, but it caused a notching effect in thin, unidirectional specimens that resulted in a strength decrease. The anodizing process can, however, be used on crossplied material or unidirectional material of substantial size where the small dissolution of fibers would not seriously degrade tensile strength. Of the organic coatings examined, the polyimide was only partially effective, and it required a high-temperature bake cycle. The silicone coating was completely in effective.

Table 2-9. Effect of Environmental Exposures and Coatings on Transverse Tensile Properties of Unidirectional B/Al

Exposure	Coating	Tensile Strength		Elastic Modulus		Percent Loss in Tensile Strength
		MN/m^2	(ksi)	GN/m^2	(msi)	
Unexposed Controls	None	156	(22.6)	103	(15.0)	
		134	(19.4)	118	(17.1)	
		134	(19.4)	152	(22.0)	
		142	(20.6)	150	(21.7)	
		118	(17.1)	141	(20.4)	
		137	(19.8)	133	(19.2)	
Low-Temperature, 500-Hour Salt Spray	None	109	(15.8)	115	(16.7)	
		117	(17.0)	124	(18.0)	
		113	(16.4)	120	(17.4)	17
Low-Temperature, 500-Hour Salt Spray	Acrylic	155	(22.5)	161	(23.4)	
		164	(23.8)	139	(20.1)	
		160	(23.2)	150	(21.8)	0
Low-Temperature, 500-Hour Salt Spray	Polyure-thane	151	(21.9)	130	(18.8)	
		170	(24.7)	152	(22.1)	
		161	(23.3)	141	(20.5)	0
Low-Temperature, 3-Month Seashore	None	112	(16.3)	119	(17.3)	
		139	(20.2)	119	(17.3)	
		148	(21.5)	139	(20.2)	
		133	(19.3)	126	(18.3)	3
Low-Temperature, 3-Month Seashore	Acrylic	126	(18.3)	123	(17.9)	
		125	(18.1)	106	(15.4)	
		121	(17.5)	109	(15.8)	
		124	(18.0)	113	(16.4)	9
Low-Temperature, 3-Month Seashore	Polyure-thane	121	(17.6)	111	(16.1)	
		149	(21.6)	112	(16.3)	
		114	(16.5)	106	(15.4)	
		128	(18.6)	110	(15.9)	6
High-Temperature, 500-Hour Salt Spray	None	106	(15.3)	—	—	
		127	(18.4)	124	(18.0)	
		117	(16.9)	124	(18.0	15

Table 2-9. Effect of Environmental Exposures and Coatings on Transverse Tensile Properties of Unidirectional B/Al, Continued

Exposure	Coating	Tensile Strength MN/m^2	Tensile Strength (ksi)	Elastic Modulus GN/m^2	Elastic Modulus (msi)	Percent Loss in Tensile Strength
High-Temperature, 500-Hour Salt Spray	Anodize	79	(11.5)	78	(11.3)	
		84	(12.2)	102	(14.8)	
		82	(11.9)	90	(13.1)	40
High-Temperature, 500-Hours Salt Spray	Silicone	31	(4.6)	—	—	
		43	(6.3)	—	—	
		33	(4.8)	—	—	75
High-Temperature, 500-Hour Salt Spray	Polyimide	105	(15.2)	117	(17.0)	
		97	(14.0)	132	(19.8)	
		101	(14.6)	127	(18.4)	26
High-Temperature, 3-Month Seashore	None	109	(15.8)	115	(16.7)	
		117	(17.0)	124	(18.0)	
		113	(16.4)	120	(17.4)	17
High-Temperature, 3-Month Seashore	Anodize	110	(16.0)	—	—	
		74	(10.7)	103	(15.0)	
		117	(16.9)	97	(14.0)	
		100	(14.5)	100	(14.5)	26
High-Temperature, 3-Month Seashore	Silicone	87	(12.6)	110	(16.0)	
		76	(11.0)	75	(10.8)	
		88	(12.8)	103	(15.0)	
		84	(12.1)	96	(13.9)	38
High-Temperature, 3-Month Seashore	Polyimide	112	(16.3)	156	(22.6)	
		108	(15.6)	125	(18.1)	
		119	(17.3)	124	(18.0)	
		113	(16.4)	135	(19.6)	17

It should also be pointed out that no serious degradation occurred with the uncoated specimens during both low- and high-temperature cycling; the predominant area of corrosion occurred along the edges of the specimens when both fibers and matrix were exposed. Therefore, if a system for coating the edges could be developed, it probably would not be necessary to coat the remainder of the composite.

For low-temperature environments, either the polyurethane or acrylic coating systems are recommended. For high-temperature applications where large pieces or crossplied material is to be used, the chromic acid anodizing process is recommended. It is also possible, under certain circumstances (such as conditions where composite edges are protected or edge surface area is small in relation to the entire structure), to use uncoated B/Al in both the high- and low-temperature environments.

2.5 MATERIAL PROCUREMENT AND QUALITY CONTROL

This section describes the procurement and quality assurance testing of all the boron/aluminum composite material used in this program. Quality assurance testing consisted of nondestructive evaluation and mechanical property testing.

2.5.1 MATERIAL PROCUREMENT. Preliminary material requirements for the entire program were determined at contract go-ahead. Requests for quotes were then sent to the two major suppliers of boron/aluminum consolidated (diffusion bonded) sheet material. It was requested that bids be returned in the following manner:

Type of Bid	Quantity
Best Effort Basis	Item Group Total
To Specification	Item Group Total

It was found that a savings of approximately 13% could be realized by placing the entire order at one time; purchasing to a specification raised the price 8%. It was believed that the state-of-the-art of composite panel fabrication was sufficiently advanced to permit the purchase of raw material to a specification. Therefore, the decision was made to place the entire order (to a specification) at one time with the option to change panel dimensions, as required, at no cost if the total weight and layup configuration of the order remained constant. Table 2-10 indicates the material ordered during the entire program. The specification, including modifications, is included in the Appendix of this report.

2.5.2 NONDESTRUCTIVE EVALUATION. All of the B/Al composite material used on this program was nondestructively evaluated prior to utilization. This approach ensured the inclusion of only the highest quality material in the program.

Convair Aerospace has had extensive experience in evaluating composite bond quality and fiber integrity, both in metallic and nonmetallic composites (References 1 through 7 and 11 through 21). It has been found that the most useful routine tests for com-

Table 2-10. Composite Materials Purchased

Phase	Group/ Item	Panel Size cm	Panel Size (in.)	Fiber Orientation	Order Released	Material Received	Panel No.
I	I-00	30 x 30 x 0.13	(12 x 12 x 0.050)	UD	X	X	MA-1
I	I-0	30 x 30 x 0.13	(12 x 12 x 0.050)	UD	X	X	MA-2
III	I-1	30 x 46 x 0.13	(12 x 18 x 0.050)	UD	X	X	PD-4
III	I-3	30 x 61 x 0.38	(12 x 24 x 0.150)	UD	X	X	PD-1
III	I-4	30 x 61 x 0.43	(12 x 24 x 0.170)	0-90 CP	X	X	PDX-2
I	I-5	30 x 76 x 0.13	(12 x 30 x 0.050)	UD	X	X	ME-1
I	I-5	30 x 76 x 0.13	(12 x 30 x 0.050)	UD	X	X	ME-2
I	I-5	30 x 76 x 0.13	(12 x 30 x 0.050)	UD	X	X	ME-3
III	I-6	30 x 46 x 0.13	(12 x 18 x 0.050)	UD	X	X	PD-6
I	I-7	30 x 30 x 0.13	(12 x 12 x 0.050)	0-90 CP	X	X	MEX-1
I	I-7	30 x 30 x 0.13	(12 x 12 x 0.050)	0-90 CP	X	X	MEX-2
I	I-7	30 x 30 x 0.13	(12 x 12 x 0.050)	0-90 CP	X	X	MEX-3
III	I-8	30 x 61 x 0.23	(12 x 24 x 0.090)	0-90 CP	X	X	PDX-3
I-III	I-9	30 x 46 x 0.05	(12 x 18 x 0.020)	UD	X	X	PD-5
I	I-10	30 x 46 x 0.13	(12 x 18 x 0.050)	UD	X	X	ME-4
I	I-11	30 x 30 x 0.13	(12 x 12 x 0.050)	0-90 CP	X	X	MEX-4
III	I-13	15 x 61 x 0.38	(6 x 24 x 0.150)	UD	X	X	PD-8
III	I-14	15 x 122 x 0.43	(6 x 48 x 0.170)	0-90 CP	X	X	PDX-4
III	I-15	25 x 61 x 1.3	(10 x 24 x 0.500)	UD	X	X	PD-9
I	I-16	30 x 46 x 0.13	(12 x 18 x 0.050)	UD	X	X	ME-5
I	I-17	30 x 30 x 0.13	(12 x 12 x 0.050)	0-90 CP	X	X	MEX-5
III	I-18	15 x 20 x 1.3	(6 x 8 x 0.500)	UD	X	X	PD-7
III	I-19	15 x 50 x 0.43	(6 x 20 x 0.170)	0-90 CP	X	X	PDX-1
III	II-1	24 x 32 x 1.3	(9.5 x 12.5 x 0.500)	UD	X	X	SC-1
III	II-2	57 x 57 x 0.15	(22.5 x 22.5 x 0.060)	UD	X	X	SC-2
III	II-3	30 x 64 x 0.5	(12 x 25 x 0.200)	±45 CP	X	X	SCX-1
III	II-4	39 x 58 x 0.5	(15.5 x 23 x 0.200)	±45 CP	X	X	SCX-2
III	II-5	39 x 39 x 0.3	(15.5 x 15.5 x 0.100)	±45 CP	X	X	SCX-3
III	II-6	30 x 28 x 0.5	(12 x 11 x 0.200)	UD	X	X	SC-3
III	III-1	47 x 74 x 0.3	(18.5 x 29 x 0.100)	±45 CP	X	X	SCX-4
III	A	14 x 29 x 0.2	(5.5 x 11.5 x 0.080)	UD	X	X	SC-4
IV	SJ-1	25.4 x 30.5 x 0.6	(10 x 12 x 0.217)	±45 CP	X	X	SJ-1
IV	SJ-2	30.5 x 30.5 x 0.2	(12 x 12 x 0.068)	UD	X	X	SJ-2
IV	SJ-3	15 x 61 x 0.1	(6 x 24 x 0.035)	UD	X	X	SJ-3
IV	IV-1A	0.17 x 43 x 101	(0.068 x 16.5 x 39.0)	UD	X	X	SB-1
IV	IV-1B	0.17 x 43 x 101	(0.068 x 16.5 x 39.0)	UD	X	X	SB-2
IV	IV-2A	0.17 x 41 x 94	(0.068 x 16.0 x 36.0)	UD	X	X	SB-8
IV	IV-2B	0.17 x 41 x 94	(0.068 x 16.0 x 36.0)	UD	X	X	SB-9
IV	IV-3A	0.17 x 36 x 94	(0.068 x 14.0 x 36.0)	UD	X	X	SB-5
IV	IV-3B	0.17 x 36 x 94	(0.068 x 14.0 x 36.0)	UD	X	X	SB-6
IV	IV-4	0.17 x 20 x 65	(0.068 x 7.0 x 24.5)	UD	X	X	SB-3
IV	IV-5	0.28 x 28 x 120	(0.109 x 11.0 x 46.5)	±45 CP	X	X	SBX-1
IV	IV-6	0.26 x 28 x 115	(0.102 x 11.0 x 43.5)	UD	X	X	SB-7
IV	IV-7,8	0.52 x 5 x 104	(0.204 x 2.0 x 41.0)	UD	X	X	SB-4
IV	IV-9	Tapered Cap		UD	X	X	SB-13
IV	IV-10	0.55 x 48 x 117	(0.217 x 19.0 x 44.5)	±45 CP	X	X	SBX-3
IV	IV-11	0.55 x 55 x 117	(0.217 x 21.5 x 44.5	±45 CP	X	X	SBX-2
IV	IV-12	0.17 x 38 x 94	(0.068 x 15 x 36)	UD	X	X	SB-10
IV	IV-13	0.17 x 38 x 94	(0.068 x 15 x 36)	UD	X	X	SB-11
IV	IV-14	0.17 x 43 x 94	(0.068 x 16.5 x 36)	UD	X	X	SB-12
IV	IV-15	0.17 x 30 x 99	(0.068 x 12 x 38)	UD	X	X	SB-14
V	V-1	0.24 x 17 x 61	(0.094 x 6.5 x 24)	UD	X	X	CP-1
V	V-2	0.24 x 15 x 8	(0.094 x 6 x 3)	UD	X	X	CP-2
V	V-3	0.24 x 18 x 61	(0.094 x 7 x 24)	UD	X	X	CP-4
V	V-4	0.24 x 25 x 211	(0.094 x 10 x 83)	UD	X	X	CP-5
V	V-5	0.24 x 15 x 8	(0.094 x 6 x 3)	UD	X	X	CP-3
V	V-6	0.18 x 46 x 18	(0.07 x 18 x 7)	0, ±45 CP	X	X	CP-6
V	V-7	0.24 x 22 x 210	(0.094 x 8.5 x 82)	UD	X	X	CP-7
V	V-8	0.24 x 22 x 210	(0.094 x 8.5 x 82)	UD	X	X	CP-8
V	V-9	0.24 x 22 x 210	(0.094 x 8.5 x 82)	UD	X	X	CP-9
V	V-10	0.24 x 22 x 210	(0.094 x 8.5 x 82)	UD	X	X	CP-10
V	V-11	0.24 x 22 x 210	(0.094 x 8.5 x 82)	UD	X	X	CP-11
V	V-12	0.18 x 203 x 76	(0.07 x 80 x 30)	0, ±45 CP	X	X	CP-12

posites have been ultrasonic C-scan and radiography. These tests have included flat panels (both unidirectional and crossplied) and structural shapes such as angles, T-, I-, and hat-sections.

Because of the increased thickness of the composite panels used in this program, it was impractical to use radiography — there are too many fibers (per unit area) to allow adequate examination. Experience has indicated that there is usually no (physical) fiber damage during pressing; however, when there was a question of damage, it was possible to examine the suspected area of a given panel radiographically.

All the composite panels were nondestructively evaluated by ultrasonic testing. The ultrasonic technique was pulse-reflection through-transmission with a single short-focused, 5 Mhz lithium sulfate transducer. The results are recorded on a C-scan recording wherein shades of gray lighter than some maximum are relatable to acoustic transmission losses within the test panel. The overall integrity of a test panel is described by an arbitrary rating system with numerical values from 0 to 5 assigned on the basis of Convair's experience in ultrasonic testing of hundreds of composite panels. The rating reflects variations from normal conditions. Normal does not necessarily mean perfect. For example, a few widely scattered stray boron filament fragments have no measurable effect on the structural performance of a given component. Although undesired from a workmanship standpoint, if small isolated defects cause no secondary effects, they are judged to be normal. Degrees of variation from normalcy are subjectively determined by engineers with wide experience in the evaluation of composite materials. Ratings of 3, 4, and 5 represent severe or widespread defects judged to have detrimental effects upon the structural performance of the component. Ratings of 1 or 2 relate to scattered or isolated defects caused by faulty workmanship or minor loss of process control. These ratings apply to defects that should not adversely affect the structural performance of the component.

Although this method of reporting the data has limitations, no other means, short of extensive computer aided data reduction, are currently available for analysis of nondestructive test data of composite materials. Precise standards that objectively relate nondestructive test data to performance data are highly desirable. However, developing these standards would require extensive effort well beyond the scope of this program.

Table 2-11 summarizes the ultrasonic test results on the composite panels.

2.5.3 MECHANICAL PROPERTY TESTING. Mechanical property testing consisted of tensile tests and flexural fatigue tests. Tensile tests were made to assure that the static tensile strength and elastic modulus of each B/Al composite panel met minimum specification requirements. Flexural fatigue tests were performed to assure well bonded material since poorly bonded material had been found to delaminate during flexural fatigue. Mechanical property test results are given in Table 2-12.

Table 2-11. Nondestructive Evaluation Results

Rating 0 = Normal
Ratings 1-5 = Deviation From Normal in Increasing Severity

Component Identification	Size cm	Size (in.)	Filament Orientation	Ultrasonic Test Rating	Remarks
MA-1	30 x 30 x 0.12	(12 x12 x 0.050)	UD	0	
MA-2	30 x 30 x 0.12	(12 x12 x 0.050)	UD	0	
ME-1	30 x 78 x 0.12	(12 x31 x 0.050)	UD	0	
ME-2	30 x 78 x 0.12	(12 x31 x 0.050)	UD	0	
ME-3	30 x 78 x 0.12	(12 x31 x 0.050)	UD	1	Light scattered linears, except 2 full length linears, 1/3 from each edge
ME-4	30 x 38 x 0.12	(12 x15 x 0.050)	UD	0	
ME-5	30 x 46 x 0.12	(12 x18 x 0.050)	UD	0	
MEX-1	30 x30 x 0.14	(12 x12 x 0.056)	0-90 CP	0	Except 1 cm along 1 edge
MEX-2	30 x 30 x 0.14	(12 x12 x 0.056)	0-90 CP	0	Minor linear indications
MEX-3	30 x 30 x 0.14	(12 x12 x 0.056)	0-90 CP	1	Except linears up to 10 cm from 1 end
MEX-4	30 x 30 x 0.14	(12 x12 x 0.056)	0-90 CP	0	
MEX-5	30 x 30 x 0.14	(12 x12 x 0.056)	0-90 CP	0	
PD-1	32 x62 x 0.38	(12 x24 x 0.146)	UD	1	Linear indications
PD-4	30 x 46 x 0.12	(12 x18 x 0.048)	UD	1	Linear indications
PD-5	30 x 46 x 0.05	(12 x18 x 0.021)	UD	0	Except 2 areas approximately 2 x 7 cm, 1 end
PD-6	31 x 46 x 0.12	(12 x18 x 0.048)	UD	0	Minor linear indications
PD-7	16 x 21 x 1.3	(6 x 8 x 0.520)	UD		
PD-8	15 x 61 x 0.4	(6 x 24 x 0.150)	UD	2	Linear indications
PD-9	27 x 62 x 1.3	(10 x24 x 0.490)	UD	0	Except approximately 2 cm along each edge
PDX-1	16 x52 x 0.43	(6 x 20 x 0.168)	0-90 CP	0	Except approximately 0.6 cm around edges
PDX-2	32 x 62 x 0.44	(12 x24 x 0.174)	0-90 CP	1	
PDX-3	32 x 62 x 0.22	(12 x24 x 0.088)	0-90 CP	0	
PDX-4	16 x 123 x 0.42	(6 x 48 x 0.167)	0-90 CP	3	Approximately 1/2 panel, remainder rated 1
SC-1	25.4 x 33.1 x 1.23	(10 x 13 x 0.485)	UD	0	Except approximately 1.5 cm along long edges
SC-2	58.5 x 58.5 x 0.15	(23 x 23 x 0.059)	UD	0	
SC-3	31.8 x 29.2 x 0.503	(12.5 x 11.5 x 0.198)	UD	0	
SC-4	15.2 x 30.5 x 0.198	(6 x 12 x 0.078)	UD	0	Except approximately 1 cm around edges
SCX-1	63.5 x 39.5 x 0.468	(25 x12 x 0.184)	±45 CP	4	Soft overall. Sent back to vendor and repressed
SCX-2	58.5 x 39.4 x 0.475	(23 x 15.5 x 0.187)	±45 CP	1	Scattered linears
SCX-3	40.7 x 40.7 x 0.277	(16 x 16 x 0.109)	±45 CP	4	Soft overall; sent back to vendor and repressed
SCX-4	48.3 x 75.0 x 0.272	(19 x 29.5 x 0.107)	±45 CP	2	Scattered soft

Table 2-11. Nondestructive Evaluation Results, Contd

Rating 0 = Normal
Ratings 1-5 = Deviation From Normal in Increasing Severity

Component Identification	Size cm	Size (in.)	Filament Orientation	Ultrasonic Test Rating	Remarks
SJ-1	25 × 30 × 0.528	(10 × 12 × 0.207)	± 45° CP	0	Light spot indications - one side
SJ-2	30 × 30 × 0.173	(12 × 12 × 0.068)	UD	0	
SJ-3	15 × 61 × 0.1	(6 × 24 × 0.035)	UD	0	
SB-1	41 × 98 × 0.168	(16.25 × 39 × 0.066)	UD	0	
SB-2	41 × 98 × 0.168	(16.25 × 39 × 0.066)	UD	0	
SB-3	17.8 × 62×0.170	(7 × 24.5 × 0.067)	UD	0	
SB-4	6.4 × 104 × 0.508	(2.5 × 41 × 0.200)	UD	0	
SB-5	34 × 91 × 0.17	(13.5× 36 × 0.068)	UD	0	
SB-6	34 × 91 × 0.17	(13.5 × 36 × 0.068)	UD	1	Light spot indications - one side
SB-7	29 × 114 × 0.26	(11.5 × 45 × 0.103)	UD	0	
SB-8	42 × 94 × 0.170	(16.5 × 37 × 0.067)	UD	0	
SB-9	42 × 94 × 0.170	(16.5 × 37 × 0.067)	UD	0	
SB-10	38 × 92 × 0.173	(15 × 36 × 0.068)	UD	1	Intermittent light areas (small)
SB-11	38 × 92 × 0.173	(15 × 36 × 0.068)	UD	0	
SB-12	42 × 92 × 0.173	(16.5 × 36 × 0.068)	UD	0	
SB-13	Tapered Cap		UD	0	
SB-14	30 × 97 × 0.173	(12 × 38 × 0.068)	UD	0	
SBX-1	28 × 118 × 0.27	(11 × 46.5 × 0.107)	± 45° CP	0	
SBX-2	55 × 113 × 0.551	(21.5 × 44.5 × 0.217)	± 45° CP	1	Few light splotches
SBX-3	48 × 113 × 0.551	(19 × 44.5 × 0.217)	± 45° CP	0	
CP-1	17 × 61 × 0.24	(6 × 24 × 0.094)	UD	0	
CP-2	15 × 8 × 0.25	(6 × 3 × 0.1)	UD	0	
CP-3	15 × 8 × 0.25	(6 × 3 × 0.1)	UD	1	Slightly nonuniform at edge and center
CP-4	18 × 64 × 0.25	(7 × 25 × 0.1)	UD	0	Only edge problem
CP-5	25 × 211 × 0.25	(10 × 83 × 0.1)	UD	1	Few light areas (small for panel size)
CP-6	0.18 × 46 × 18	(0.07 × 18 × 7)	0, ± 45° CP	0	
CP-7	0.24 × 22 × 210	(0.094 × 8.5 × 82)	UD	0	
CP-8	0.24 × 22 × 210	(0.094 × 8.5 × 82)	UD	1	1 cross indication
CP-9	0.24 × 22 × 210	(0.094 × 8.5 × 82)	UD	1	
CP-10	0.24 × 22 × 210	(0.094 × 8.5 × 82)	UD	1	Spots in middle only
CP-11	0.24 × 22 × 210	(0.094 × 8.5 × 82)	UD	1	Few intermittent light spots
CP-12	0.8 × 203 × 76	(0.07 × 80 × 30)	0, ± 45° CP	0	Except CP shading. Radiographs taken of selected defects; damage judged insignificant and panel accepted

Table 2-12. Quality Assurance Mechanical Property Test Results

Component Identification	Size cm	Size (in.)	Filament Orientation	Tensile Strength MN/m^2	Tensile Strength (ksi)	Elastic Modulus GN/m^2	Elastic Modulus (msi)	Flexural Fatigue Cycles to Failure*
PD-1	30 × 62 × 0.38	(12 × 24 × 0.146)	UD	1317	191	215	31.3	3.2×10^6
PD-4	30 × 46 × 0.12	(12 × 18 × 0.048)	UD	1482	215	220	31.9	$>2 \times 10^7$**
PD-5	30 × 46 × 0.05	(12 × 18 × 0.021)	UD	1434	208	226	32.8	**
PD-6	30 × 46 × 0.12	(12 × 18 × 0.048)	UD	1524	221	217	31.5	**
PD-7	15 × 21 × 1.3	(6 × 8 × 0.520)	UD	1227	178	206	29.9	$> 10^7$
PD-8	15 × 61 × 0.4	(6 × 24 × 0.150)	UD	1289	187	216	31.3	$> 10^7$
PD-9	25 × 62 × 1.3	(10 × 24 × 0.490)	UD	1282	186	210	30.5	$>7.1 \times 10^6$
PDX-1	15 × 52 × 0.43	(6 × 20 × 0.168)	0-90 CP	208	30.1	86	12.4	4.5×10^5***
PDX-2	30 × 62 × 0.44	(12 × 24 × 0.174)	0-90 CP	190	27.6	111	16.1	<1000***
PDX-3	30 × 62 × 0.22	(12 × 24 × 0.088)	0-90 CP	238	34.5	112	16.2	$>10^7$
PDX-4	15 × 123 × 0.42	(6 × 48 × 0.167)	0-90 CP	244	35.4	112	16.3	1.5×10^6
SC-1	25 × 33 × 1.23	(10 × 13 × 0.485)	UD	1282	186	210	30.5	$>6.5 \times 10^6$
SC-2	58 × 58 × 0.15	(23 × 23 × 0.059)	UD	1455	211	222	32.2	**
SC-3	32 × 29 × 0.503	(12.5 × 11.5 × 0.198)	UD	1269	184	230	33.4	$>9.2 \times 10^6$
SC-4	15 × 30.5 × 0.198	(6 × 12 × 0.078)	UD	1627	236	248	36.0	**
SCX-1	63.5 × 39.5 × 0.468	(25 × 12 × 0.184)	±45 CP	367	53.2	160	23.2	$>9.8 \times 10^6$
SCX-2	58 × 39 × 0.475	(23 × 15.5 × 0.187)	±45 CP	408	59.2	126	18.2	$> 10^7$
SCX-3	41 × 40 × 0.277	(16 × 16 × 0.109)	±45 CP	250	36.3	108	15.6	$> 10^7$
SCX-4	48 × 75 × 0.272	(19 × 29.5 × 0.107)	±45 CP	377	54.6	138	20.0	$> 10^7$
SB-1	41 × 98 × 0.168	(16.25 × 39 × 0.066)	UD	1420	206	217	31.5	**
SB-2	41 × 98 × 0.168	(16.25 × 39 × 0.066)	UD	1538	223	222	32.2	**
SB-3	18 × 62 × 0.170	(7 × 24.5 × 0.067)	UD	1613	234	241	35.0	**
SB-4	6.5 × 104 × 0.508	(2.5 × 41 × 0.200)	UD	1372	199	212	30.7	$>10^7$
SB-5	34 × 91 × 0.17	(13.5 × 36 × 0.068)	UD	1538	223	201	29.2	**
SB-6	34 × 91 × 0.17	(13.5 × 36 × 0.068)	UD	1627	236	223	32.3	**
SB-7	29 × 114 × 0.26	(11.5 × 45 × 0.103)	UD	1324	192	224	32.5	**
SB-8	42 × 94 × 0.170	(16.5 × 37 × 0.067)	UD	1351	196	222	32.2	**
SB-9	42 × 94 × 0.170	(16.5 × 37 × 0.067)	UD	1241	180	207	30.0	**
SB-10	38 × 94 × 0.170	(15 × 37 × 0.067)	UD	1303	189	232	33.7	**
SBX-1	28 × 118 × 0.27	(11 × 46.5 × 0.107)	0 ±45 CP	-	-	-	-	‡
SBX-2	55 × 117 × 0.55	(21.5 × 44.5 × 0.217)	0 ±45 CP	-	-	-	-	‡
SBX-3	48 × 117 × 0.55	(19 × 44.5 × 0.217)	0 ±45 CP	384	55.7	115	16.6	
CP-5	25 × 211 × 0.25	(10 × 83 × 0.1)	UD	1572†	228	217	31.5	
CP-7	22 × 210 × 0.24	(8.5 × 82 × 0.094)	UD	1717†	249	227	32.9	
CP-8	22 × 210 × 0.24	(8.5 × 82 × 0.094)	UD	1351†	196	198	28.7	
CP-9	22 × 210 × 0.24	(8.5 × 82 × 0.094)	UD	1558†	226	216	31.3	
CP-10	22 × 210 × 0.24	(8.5 × 82 × 0.094)	UD	1503†	218	205	29.7	
CP-11	22 × 210 × 0.24	(8.5 × 82 × 0.094)	UD	1551†	225	183	26.6	

* No failures occurred by delamination of the specimen

** Too thin to test (i.e., stress level less than 50% of tensile strength)

*** Tensile failure due to overload

† Average compression strength

‡ Weld schedule specimens, insufficient material for Q. A. testing

Tensile tests were performed in the same manner as was used for the materials evaluation task and previously described in References 1, 2, and 3. Flexural fatigue tests were performed in fully-reverse ($R = -1$) bending. A Sontag SF-1U test machine with a standard bending fixture was used. In order to prevent fretting of the aluminum surface, doublers were bonded onto the ends of the specimen before testing. The test section was 5 cm (2 in.) long by 1.27 cm (0.50 in.) wide by the thickness of the specimen. Since the maximum amplitude of the machine is fixed, the stress on thin specimens was very low. Therefore, only the thicker specimens, where a stress level of approximately 50 percent of the ultimate static tensile strength could be applied, were tested. The test results are reported in Table 2-12. The failure mode of those specimens which actually failed was always some form of axial stress and not due to a shear stress (i.e., no specimen failed by delamination indicating that all of the B/Al test panels were well bonded; this agrees with the results from nondestructive testing).

SECTION 3

PROCESS DEVELOPMENT

The objective of this portion of the program was to develop and optimize both existing and new fabrication techniques for B/Al structural members and to demonstrate these techniques in assembling metal matrix structures. Primary emphasis has been on the application of conventional sheetmetal technology to metal matrix composites. Machining processes examined included advanced trimming methods for large-scale composite sheets and plates and rotary ultrasonic drilling and hole punching of B/Al components. Electroless and portable electrolytic plating methods of composite sheets were examined, and Con Braz joining, resistance welding, mechanical fastening, and adhesive bonding processes applicable to B/Al were modified and improved. Brake press forming, developed under a company-funded project, was also performed on the program.

3.1 MACHINING

Convair Aerospace has performed extensive investigations related to the machining of B/Al composite sheet material on both contracted and company-funded programs (Reference 1, Vol. II, and References 7 and 22). Evaluation has consisted of various methods and techniques of metal removal to determine the most economical and precise machining methods.

The primary tasks for large-scale fabrication that required further development at the start of the contract included the determination of a suitable edge finish in those processes applicable to large structures, a means of handling large structures, and dimensional control.

The basic machining process examined during this program was a cutoff method capable of yielding a finished edge surface. Accomplishment of this objective meant that 1) structures to be assembled did not require secondary finishing steps, and 2) final compenent machining costs were kept to a minimum.

3.1.1 <u>DIAMOND DISC CUTOFF SAW</u>. The basic machining process examined on this program was a low-cost cutoff method capable of yielding a finished edge surface so that assembled structures would not require secondary finishing steps. The selected concept for accomplishing this objective was the use of a diamond disc cutoff saw. To verify the applicability of the diamond cutoff wheel, cuts were made on thick composites, crossplied composites, and panels up to 1.8m (6 ft) in length. Measurements were made along the length of the cut to measure the degree of dimensional control that could be obtained under several operating conditions. The quality of the edge finish along the cuts was also examined.

To accomplish this machining task, a large, gantry-type unit was designed and constructed under a company sponsored program (Reference 23). The saw has an overarm carriage unit with an overall length of 3.6m (12 ft). A steel-framed table was constructed to support a 0.63 by 3.6m (2 by 12 ft) long aluminum table top. A 3.3m by 30.5 cm by 10.2 cm (11 ft by 12 in. by 4 in.) overarm steel rail contains a rack and pinion drive for moving the carriage containing the saw blade. Figure 3-1 shows an overall view of the diamond disc cutoff saw. The carriage assembly is power fed by a variable speed, reversible dc shunt wound motor with an armature speed of 0 to 4000 rpm and a 0 to 13 rpm gear shaft speed. The carriage speed ranges from 0 to 100 cm (0 to 40 in.) per minute. Adjustable stops trip a microswitch at the end of the cut and stop the carriage movement. The blade drive motor is a 1492W (2 hp), 440 volt motor geared to a 3450 rpm shaft output. Variable speeds are obtained by a V-belt pulley system. In addition to the longitudinal motion of the blade in relation to the table, a vertical and cross movement of the blade is also obtainable. Figure 3-2 shows a closeup view of the carriage assembly.

A 0.095 m^3 (25 gallon) stainless steel tank was constructed for containing the cutting fluid. A drain gutter was skirted along the entire perimeter of the table for drainage of the coolant to the tank. A 25-cm-diameter by 1.3-mm-thick (10-inch-diameter by 0.050-in.-thick) diamond-impregnated cutoff disc was purchased from Accurate Diamond Tool Co. It is a continuous-rim-type blade containing 46 grit size natural diamonds by 100 concentration with a 6.4 mm (1/4 in.) depth of diamonds. Figure 3-3 shows the cutoff blade used on the program.

In addition to performing fabrication tasks during building of composite structures, a study was made to determine the effect that cutting fluid, tool surface speed, and feed rate had on machinability. The effect of B/Al heat treatment on tool wear was also examined and compared to the effect in machining non-heat-treated composites.

3.1.1.1 <u>Cutting Fluids.</u> Various cutting fluids, including a 50-50 mixture of sulfochlorinated oil and kerosene, a water-soluble oil, and a soap with water were evaluated during the tests. Figure 3-4 shows the effect of these cutting fluids in sawing. The water-soluble oil was a mixture of water and oil at a 1 to 25 ratio. A volume of 0.06 m^3 (15 gallons) of water, 66×10^{-5} m^3 (22 fluid oz) of Ivory soap, and 1.2×10^{-4} m^3 (0.25 pint) of Dow Corning 703 silicone fluid was used for the soap and water cutting fluid. The silicone was used to minimize the sudsing effect of the soap.

3.1.1.2 <u>Heat Treatment.</u> The machining of the as-received B/Al composite material was compared to the machining of B/Al in the heat-treated condition (T-6). It was found that the condition of the matrix affected wheel wear; heat treatment causes a decrease in tool life. Figure 3-5 shows the effect of the heat-treat condition in sawing. The heat-treat sequence for the B/Al(T-6 condition) consisted of solution treatment at 799K (980F) for 30 minutes, water quenching, and aging at 450K (350F) for eight hours.

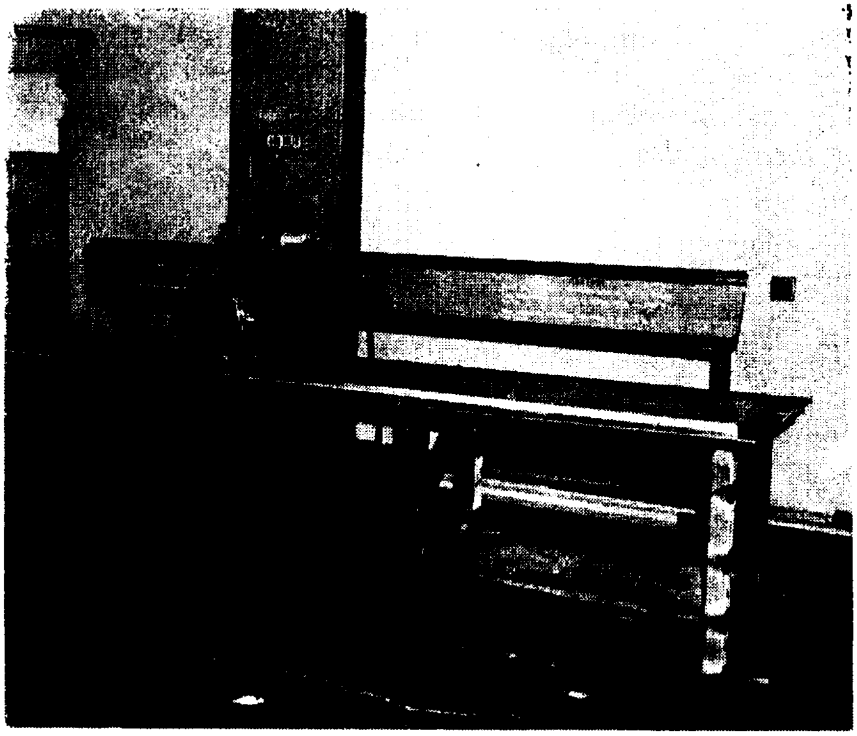


Figure 3-1. Overall View of the Diamond Disc Cutoff Saw (05600M)

Figure 3-2. Machining of a Composite Hat Section (119336B)

3.1.1.3 Feed Rate. The relationships between wheel life, amount of metal removed, and the feed rate were also examined. At a constant wheel wear of 0.05 mm (0.002 in.) on the diameter, higher feed rates result in lower amounts of material removal. Figure 3-6 illustrates this result.

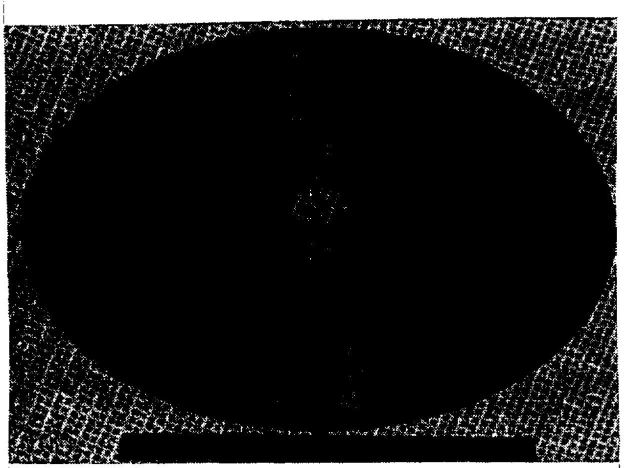


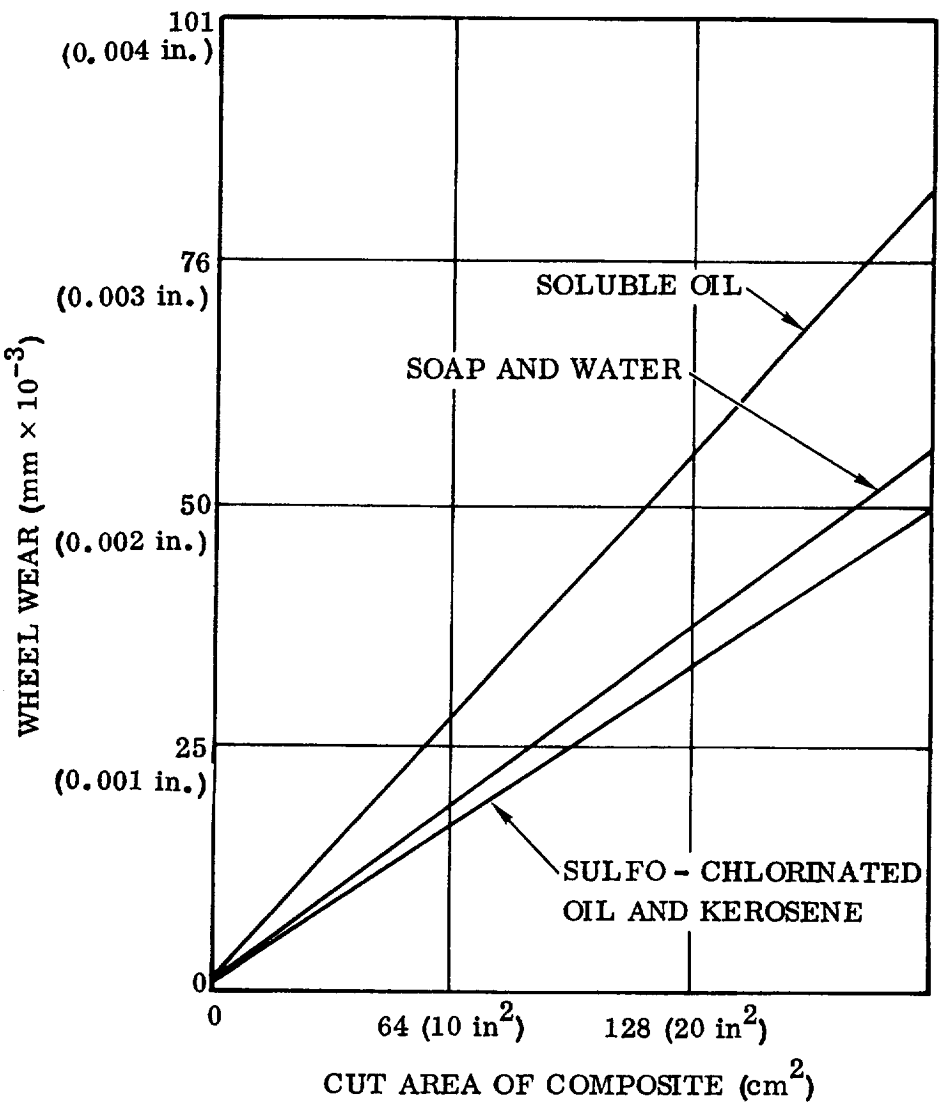
Figure 3-3. A 46 Grit Diamond Impregnated Cutoff Blade, 25 cm (10 inches) in Diameter (119338B)

3.1.1.4 Edge Finish. The edge of sawed composite material was examined to assess the extent of fiber damage during cutting. Specimens were etched in 50% by weight NaOH in water to reveal the fibers. Examination indicated that 60 to 90% of the fibers in the surface layers were damaged up to 0.25 mm (0.01 in.) in from the edge cut. The interior layers of fibers appeared unaffected. Figure 3-7 reveals the extent of edge damage in the surface layer of the composite. This damage was not considered significant, and had no effect on subsequent fabrication operations.

3.1.1.5 Face Milling. In addition to sawing of composite material, the diamond disc cutoff saw was also designed for face milling using a 28-cm (11-inch)-diameter, diamond-plated face mill. The body of the cutter was made of 7075 aluminum with a steel insert for the diamond-plated surface. A 20/40 diamond grit size was used for taking both rough and finish cuts. This configuration eliminated loading of the voids between the diamond grits. Figure 3-8 shows the completed tool ready for use. Previous work at Convair (Reference 1, Vol. II) indicated that a diamond-plated tool outperformed a diamond-impregnated tool for routing or milling operations. The diamond-plated tool exhibited a freer cutting action and loading up was kept to a minimum. To assist the cutter in maintaining a free cut and, as a result, longer tool life, a cutting fluid consisting of straight oil mixed with kerosene (50-50 mixture) was used. A cutting speed of 30 to 46 sm/min (100 to 150 sfm) was also found to increase tool life.

A typical application of the face milling operation is shown in Figure 3-9 where the cutter is milling a composite structure to a tolerance of 0.05 mm (0.002 in.).

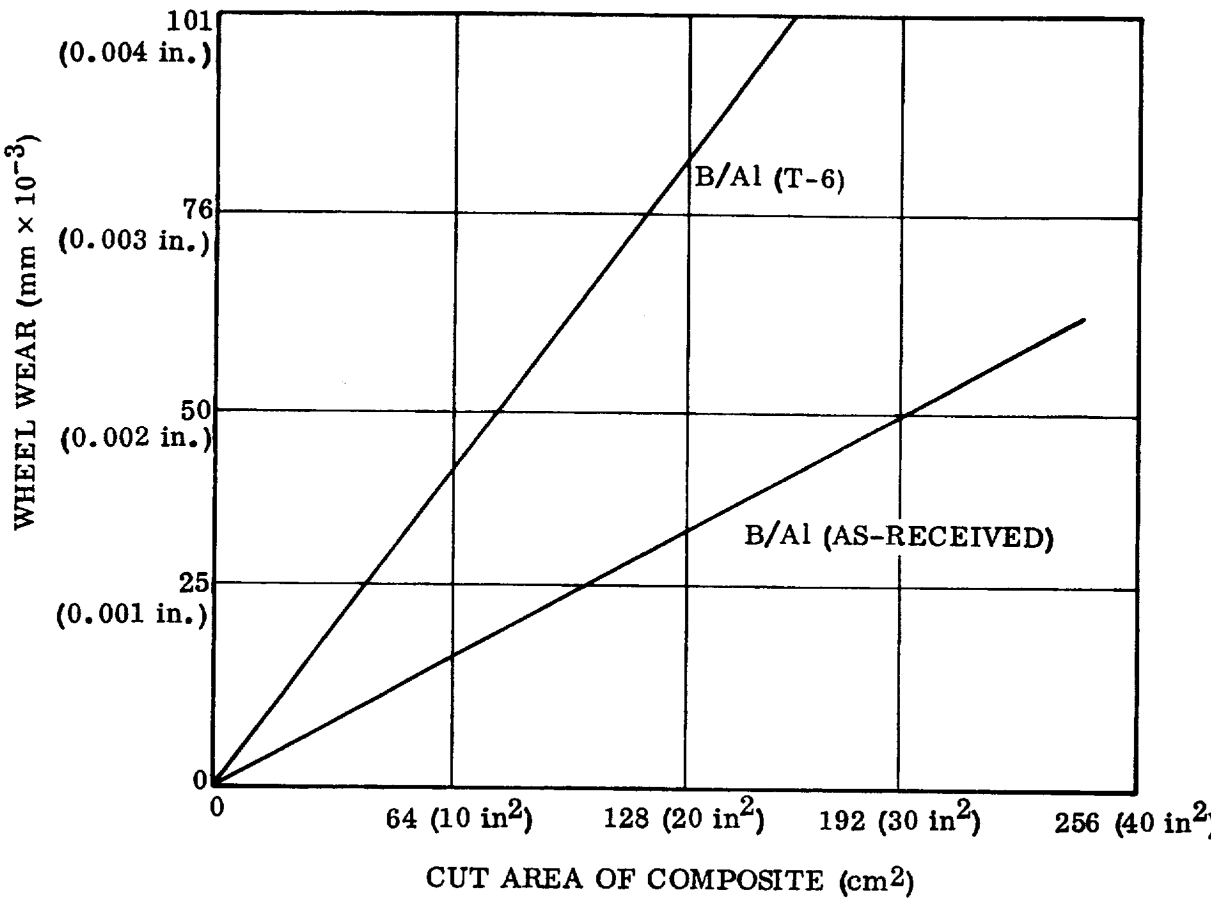
3.1.2 DRILLING OF THE SUBCOMPONENT SPECIMENS. Drilling of the subcomponent specimens was accomplished using both the rotary ultrasonic (RUSM) drilling process with diamond-impregnated core drills, and an Induma mill with high-speed-steel (HSS) twist drills.



Test Conditions

Wheel:	Diamond impregnated, 46 grit, 100 concentration
Wheel Speed:	1710 sm/min (5600 sfm)
Feed Rate:	5 cm/min (2 in/min)

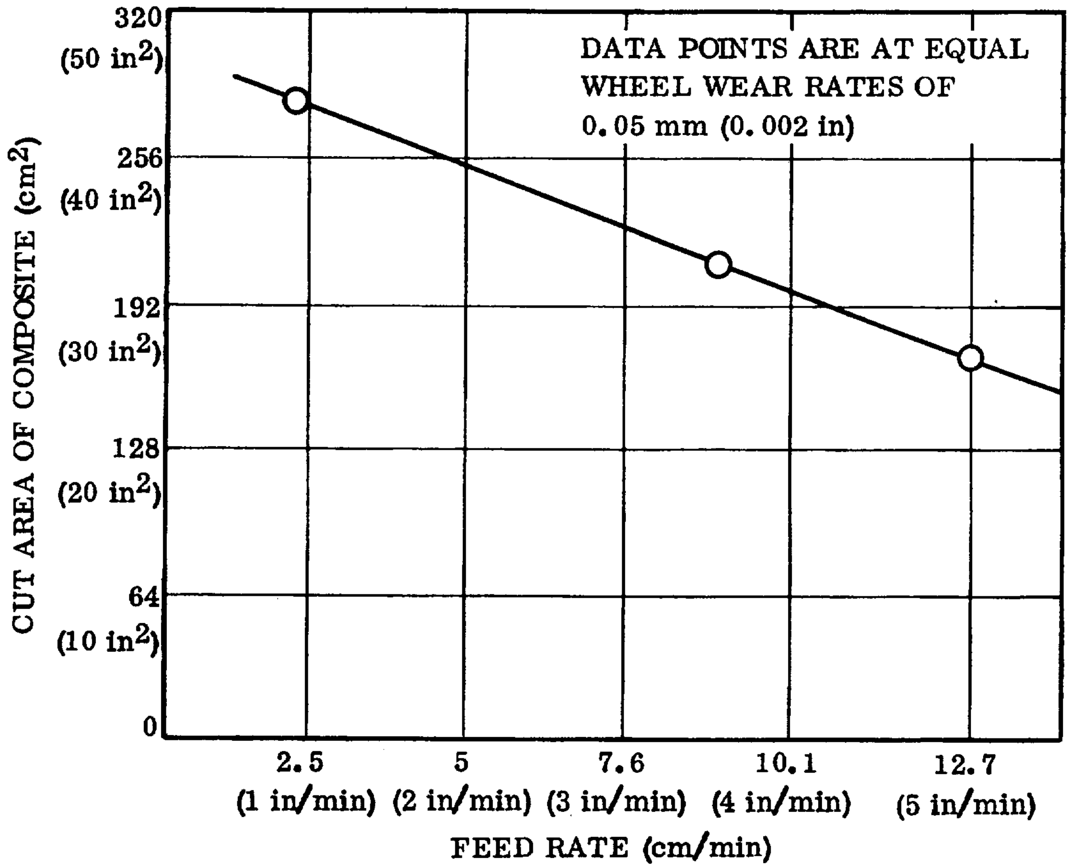
Figure 3-4. Effect of Cutting Fluids on Sawing B/Al Composite Material (As Received)



<u>Test Conditions:</u>

Wheel:	Diamond impregnated, 46 grit, 100 concentration
Wheel Speed:	1710 sm/min (5600 sfm)
Feed Rate:	13 cm/min (5 in/min)
Cutting Fluid:	Chemical Emulsion
Work Material Thickness:	0.23 cm (0.090 in.)

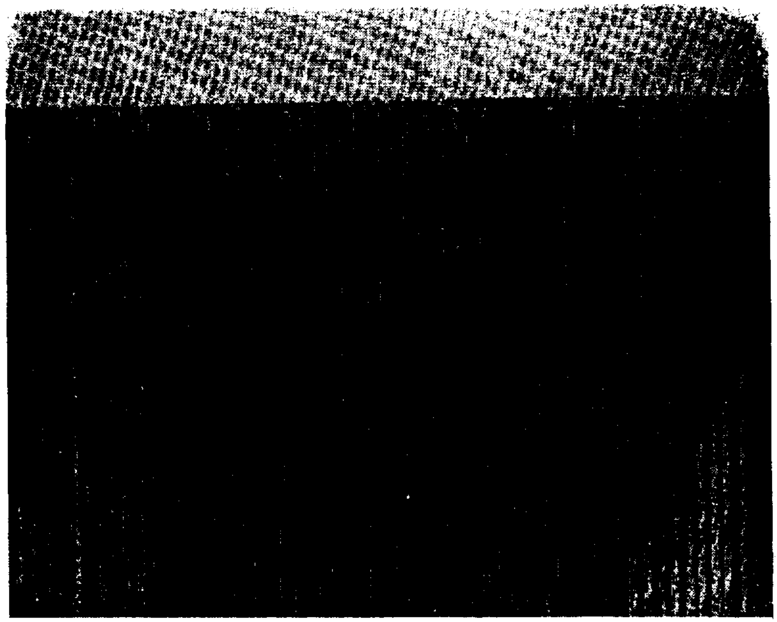
Figure 3-5. Effect of Heat-Treat Condition on Sawing B/Al Composite Material



Test Condition:

Wheel:	25 cm (10 inch) diameter, continuous rim, diamond impregnated 46 grit, 100 concentration
Wheel Speed:	1710 sm/min (5600 sfm)
Cutting Fluid:	Chemical Emulsion

Figure 3-6. Effect of Feed Rate on Sawing B/Al Composite Material (As Received)



The surface layer of aluminum has been etched away to reveal the extent of fiber damage during machining.

Figure 3-7. Edge Finish of Machined Composite Panel (D1089)

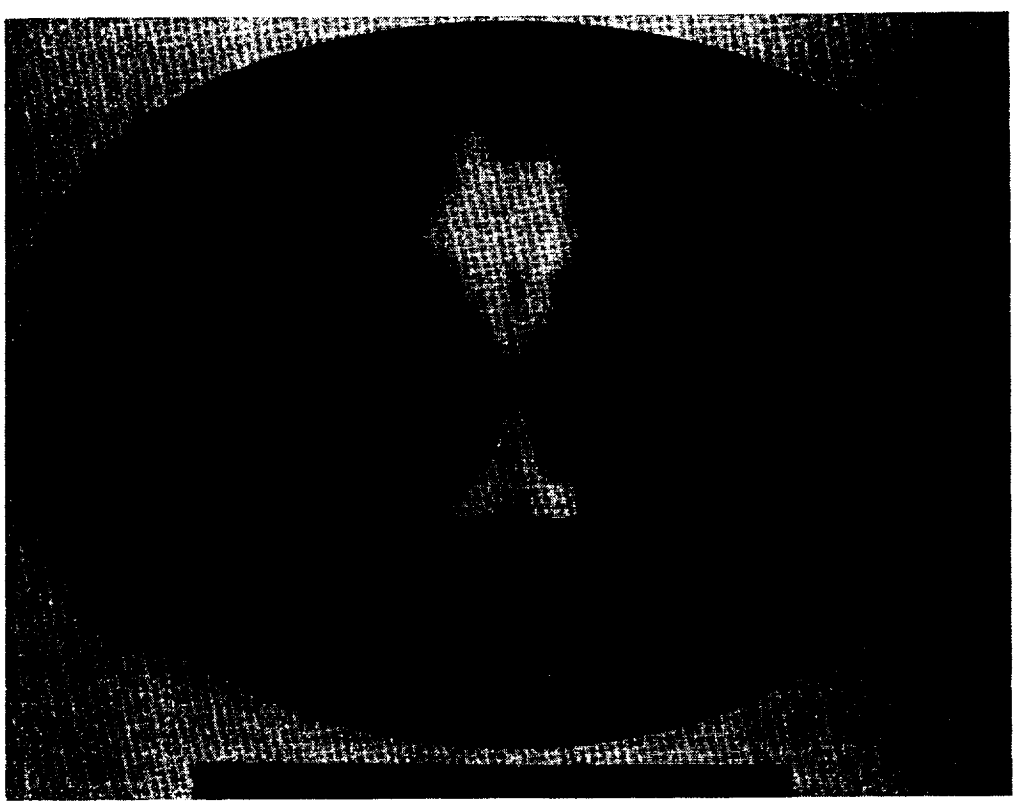


Figure 3-8. The Diamond-Plated Face Mill (119337B)

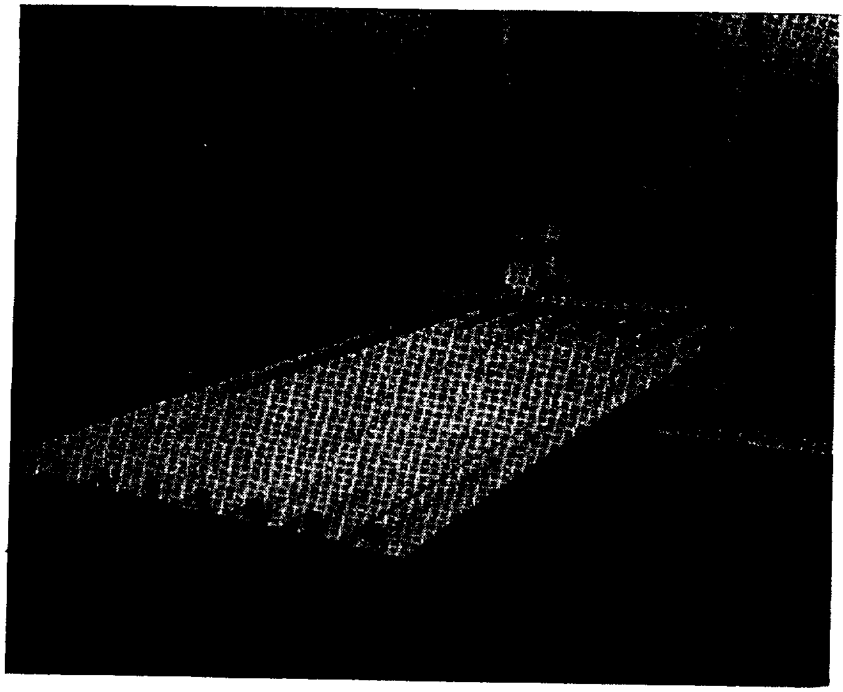


Figure 3-9. Overall View of Face Milling Operation Performed on the Diamond Disc Circular Saw Machine (124905B)

3.1.2.1 Web-to-Cap Joint (B/Al to Ti). A total of 72 close tolerance 6.3 mm (0.25 in.) diameter bolt holes were required in the three test specimens. Figure 3-10 shows one of the drilled specimens and the diamond-core drill used in the drilling operation. The drilled material was 4.8 mm (0.19 in.) thick ±45 B/Al, heat treated to the T-6 condition.

The drilling conditions used for the web-to-cap joint specimens were as follows:

Drill: 6.3 mm (0.25 in.) diameter diamond-impregnated core drill, 180 grit.

Spindle speed: 3500 rpm.

Drill penetration rate: 2.3 mm/min (0.090 in/min).

Drilling fluid: Oil and kerosene (50/50 mixture).

Hole tolerance: $6.3\ \text{mm}\ {}^{+0.12\ \text{mm}}_{-0.00\ \text{mm}} \left(0.250\ \text{in.}\ {}^{+0.005\ \text{in.}}_{-0.000\ \text{in.}}\right)$

The drilling was accomplished with one core drill for all three specimens. The average tool wear was 0.1 mm (0.0038 in.) per 24 holes drilled. The diameter of all holes was 6.4 mm (0.253 in.). Hole finish was excellent with a slight burr on the exit side of the hole. A backup material was used to minimize the burred edge. Figure 3-11 shows the amount of drill wear after every four holes drilled.

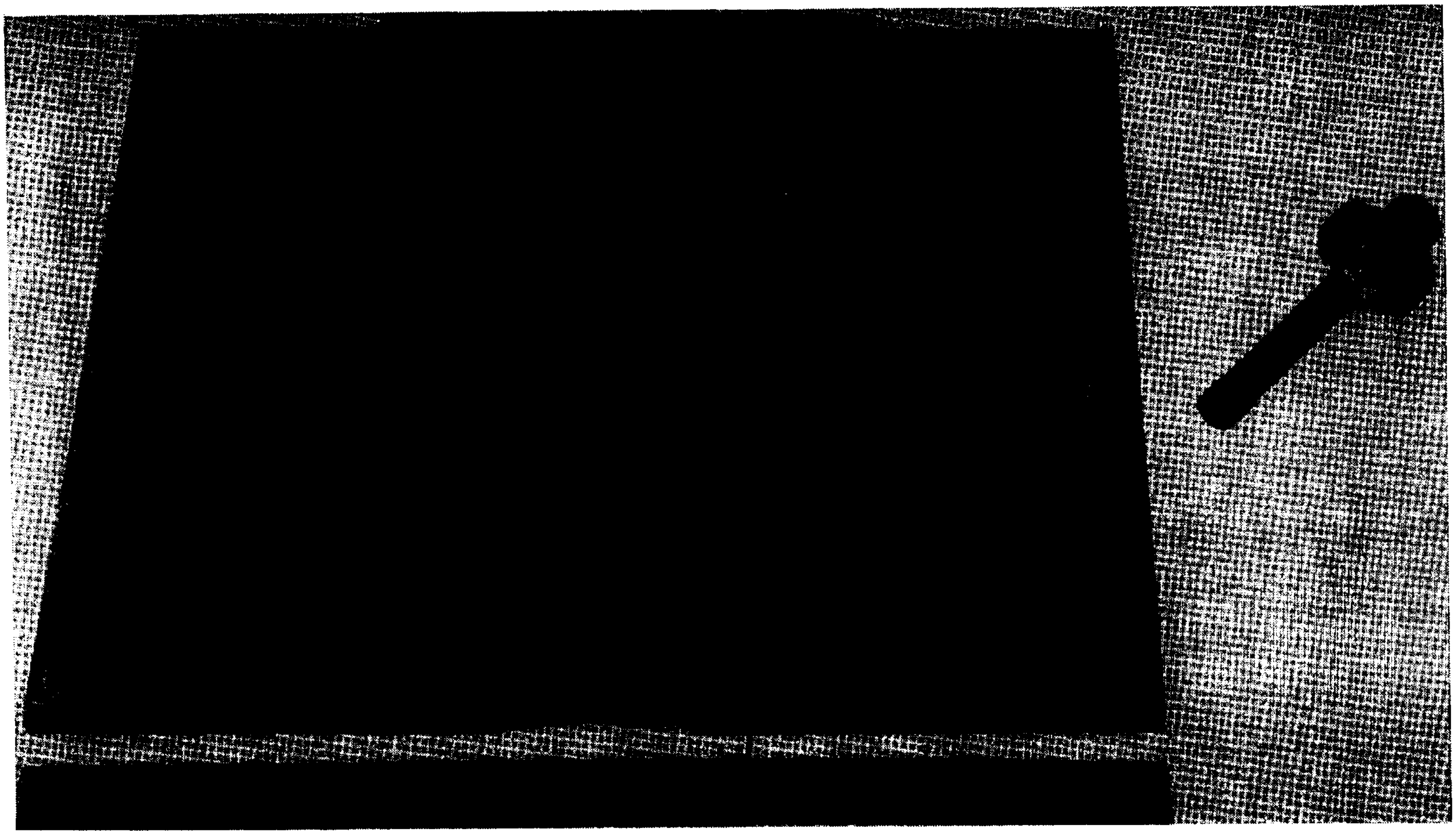


Figure 3-10. Diamond-Drilled Web-to-Cap Joint Specimen (121029B)

3.1.2.2 Tension Field Panels. A total of 68 bolt holes [8 mm (0.315 in.) diameter] were drilled in a 7.6 mm (0.300 in.) thick specimen by the RUSM process. This specimen presented a difficult drilling problem because of the necessity of drilling heat-treated B/Al sandwiched between titanium. A 7.9 mm (5/16 in.) 120 grit, diamond-impregnated core drill was used at a speed of 3250 rpm. The average drill wear was 0.02 mm (0.0012 in.) and the drilling time was seven minutes per hole.

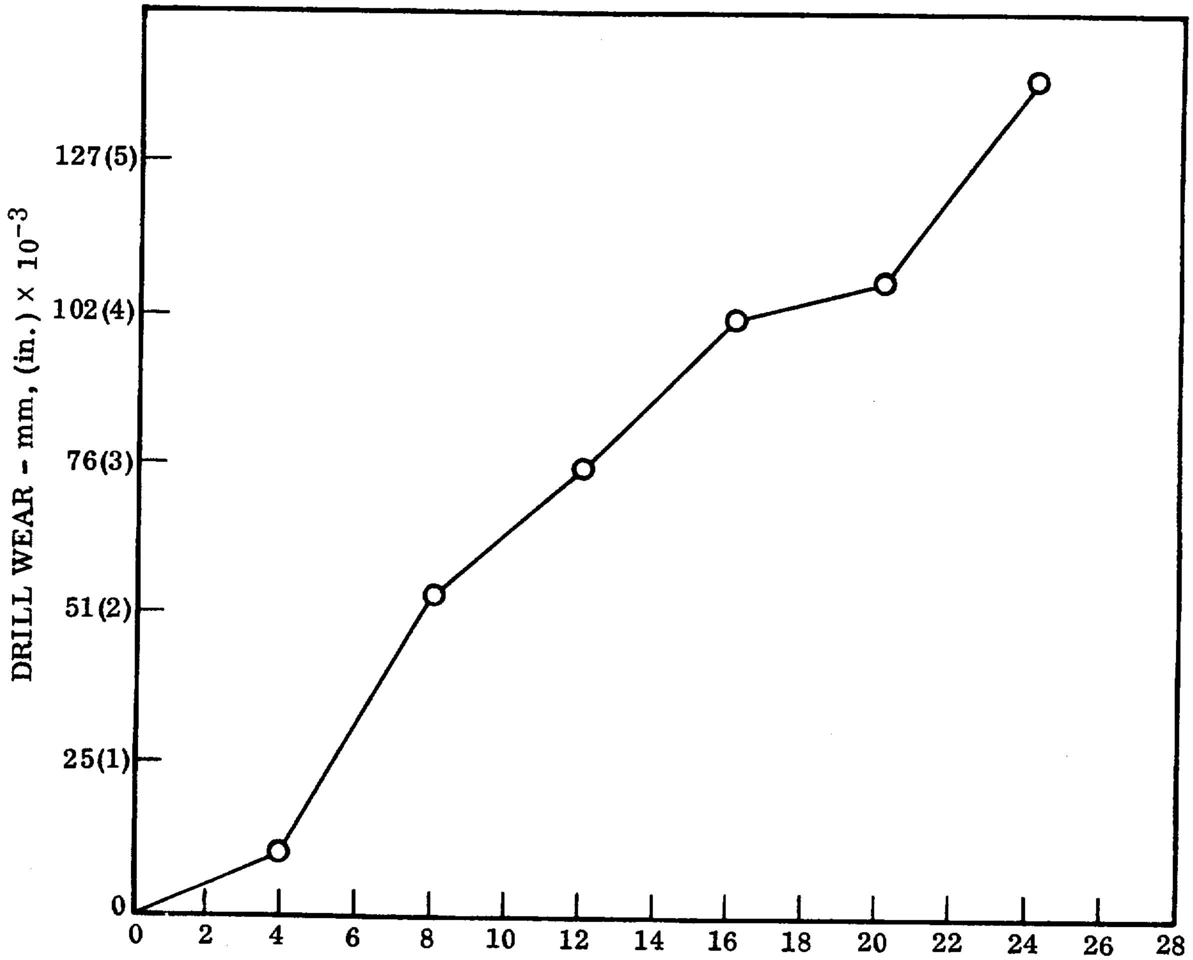


Figure 3-11. Drill Wear of RUSM Tool in 4.8 mm (0.190 in.) B/Al Heat Treated to the T-6 Condition

A second tension-field panel specimen [10.2 mm (0.400 in.) thick] was drilled using 7.9 mm (5/16 in.) diameter M-42 HSS twist drills. The drilling operation was performed on an Induma vertical milling machine. The drill time per hole averaged 35 minutes using a different drill for each hole. The drills were resharpened and used again. An average drill speed of 0.6 to 1.5 sm/min (2 to 5 sfm) was used.

3.1.2.3 Web-Splice. A total of four specimens having twenty-four 7.9 mm (5/16 in.) diameter holes and eight 6.3 mm (1/4 in.) diameter holes per specimen were drilled on the Induma milling machine using M-42 HSS twist drills. The drilling conditions were the same as those for the tension-field panel specimen.

3.1.3 HOLE PUNCHING. In addition to drilling, hole punching has proven to be a realistic and economical approach to producing holes in B/Al material up to 2.7 mm (0.108 in.) thick. The strength and fatigue life of composites having punched holes are comparable to composites having diamond-drilled holes (Reference 7). The male and female dies are inexpensive ($1.50 per die set) and are capable of producing several hundred holes. Tests were conducted on 2 mm (0.080 in.) thick $\pm 60^\circ$ B/Al in the as-received condition. After 500 holes were punched,a 6.3 mm (0.25 in.) diameter male die showed a wear of 0.3 mm (0.009 in.) on the diameter. To maintain a hole tolerance of +0.05 mm, -0.00 mm (+0.002 in., -0.000 in.), an additional reaming operation was performed using a diamond-plated twist drill. All 500 holes were brought to size using this latter method. No apparent sign of drill wear was observed.

3.1.4 COMPONENT MACHINING. A discussion of machining techniques used during fabrication of the B/Al shear beam and compression panel is presented in Section 4.

3.1.5 DISCUSSION. All raw composite sheet material received from the vendor requires edge trimming. It is recommended that material up to 1.5 mm (0.060 in.) thick be sheared when a smooth edge finish is not required; however, thicker material and material requiring a smooth square edge finish should be cut using the diamond disc cutoff saw. In addition to its sawing capabilities, this machine can be used for edge milling operations by incorporating a large-diameter, diamond-plated face mill. Studies performed on the program have demonstrated that the sawing operation is both economical and a precise method for cutting B/Al. Composite material has been readily cut using one pass (regardless of material thickness) at feed rates up to 15.2 cm/min (6 in/min). The average wheel loss was 7.0×10^{-5} meter per meter of composite material cut. It is recommended that sulpho-chlorinated oil and kerosene be used as the cutting fluid because this combination has been found to reduce tool wear. Slower feed rates will also yield longer tool life, but a trade-off must be made between tool wear and time (labor cost) per cut. Heat-treated composites cause greater tool wear than as-received composites regardless of cutting conditions.

Drilling of B/Al and B/Al combined with conventional materials constitutes a major concern in machining. As in sawing, the preferred tool material for many applications is diamond. The diamond, initially considered an expensive item, has become the most economical means for producing precise holes in metal matrix composite materials.

To achieve the best drilling results with the B/Al material, a rotary ultrasonic machine (RUSM) has been used. The primary purpose of the ultrasonic energy is to eliminate the "loading up" of matrix material on the drill, a situation encountered in machining with conventional tools. This permits the cutting edges to be exposed to the work material at all times. Countersinking for flush head rivets and bolts has also been accomplished with RUSM using a diamond tool (Reference 7). One tool may be used to prepare several thousand holes if sound countersinking techniques are observed.

There are, however, still applications where it might be more expedient to machine the composite with HSS twist drills rather than the RUSM. The decision on which process to use depends on the type of drilling required (thickness of composite and composite heat treatment), the size of the structure to be machined, drilling time limitations, the conventional materials that must be drilled in conjunction with the composite, and portability requirements of the equipment.

In addition to drilling, hole punching has proven to be a realistic and economical approch to producing holes in B/Al skins up to 2.7 mm (0.108 in.) thick. The strength and fatigue life of composites having punched holes are comparable to composites having diamond-drilled holes (Reference 7). As many as 500 holes have been punched with one set of inexpensive dies.

3.2 PLATING METHODS

The surface preparation of B/Al or titanium for brazing has been found to be instrumental in attaining highly reliable joints. It has been shown that thin nickel coatings of about 0.005 mm (0.0002 in.) thick are effective in promoting brazing ease, alloy flow, and general strength increases (Reference 7). This result is attributed to the higher wettability of the nickel surface, leading to generally better flow conditions.

Nickel plating was performed on most details before brazing because brazing of like surfaces greatly simplified the selection of the braze alloy. Two alternate plating systems were evaluated to determine their suitability for brazing the component shear beam and to compare their relative merits. These methods were electroless and Selectron plating.

3.2.1 ELECTROLESS PLATING. This is an immersion process whereby the part is totally immersed in cleaning and plating solutions. As implied, plating occurs without the application of any external electric current and nickel deposition is not dependent upon the ability of the specimen to transmit an electric current. Aluminum and B/Al have been successfully plated by this method. The plating procedure is outlined in Table 3-1.

3.2.2 SELECTRON PLATING. This process offers more versatility than chemical plating because it is not limited to small structures, it can be used to plate a large range of materials, it can be used for the electrochemical treatment of surfaces such as anodizing, and it can be used for cleaning surfaces prior to plating. The Selectron plating process is a refined brush plating technique that has been developed by Selectrons, Ltd., New York, N.Y. The process is a high-speed, selective-plating system in which the equipment can be brought to the work and where no tanks of solutions are required.

Two technicians were sent for training and instruction in the proper use of the equipment. The course was a four-day coverage on the Selectron theory and operation.

Table 3-1. Cleaning and Electroless Nickel Plating Procedure for 6061 Aluminum Foil and 6061 Matrix Composite

1. Degrease by wiping with cheesecloth and acetone or methyl ethyl ketone.
2. Precondition by soaking in ARP LP-3AL-13 deoxidizer for 30 minutes minimum or until visually uniformly clean. (LP-3AL-13, Allied Research Products, Inc., 0.125 m^3/m^3 [16 fluid oz/gal], distilled or deionized water required.)
3. Rinse in tap water.
4. Clean in Aluminetch No. 2 for one minute at room temperature. (Aluminetch No. 2, Turco Products, Inc., 0.063 m^3/m^3 [8 fluid oz/gal]).
5. Rinse in tap water.
6. Rinse in deionized water.
7. Deoxidize in ARP LP-3AL-13 for 30 minutes minimum or until soot is completely removed.
8. Rinse in tap water, then deionized water.
9. (Optional) Dip in 50% HNO_3 + 5% HF, balance H_2O for 10 seconds, rinse in deionized water.
10. Zincate part in sodium zincate solution for 30 to 45 seconds with agitation. (Sodium zincate solution is 2×10^{-3} m^3 [65 fluid ounces] ZnO + 4×10^{-3} m^3 [one gallon] 50% NaOH. Cool before using.)
11. Thoroughly rinse in tap water.
12. Immerse in HNO_3 for five to 10 seconds.
13. Rinse in tap water.
14. Zincate as in Step 2.
15. Rinse in tap water.
16. Electroless nickel plate in Anomet 24 at 352 ±1K (174 ±1F) for 10 minutes.
17. Rinse in tap water followed by rinse in deionized water and dry.
18. Bake for 60 minutes at 436K (325F) (minimum).

Note; Activate electroless nickel plate by immersion in 25% HCl at room temperature for 15 to 30 seconds prior to additional plating.

The model 3030 PD Selectron power pack was purchased and set up at Convair. Figure 3-12 shows the unit being used to nickel plate an aluminum strip. Both aluminum and B/Al composite material were nickel plated using the process. The adhesion was checked by bend tests on the aluminum and peel tests on both materials; the results all indicated a good bond. Examination of the edges of the B/Al material showed that the nickel had not been plated on the exposed boron filaments. This is typically the case where deposition is dependent on the ability of the boron to transmit an electric current.

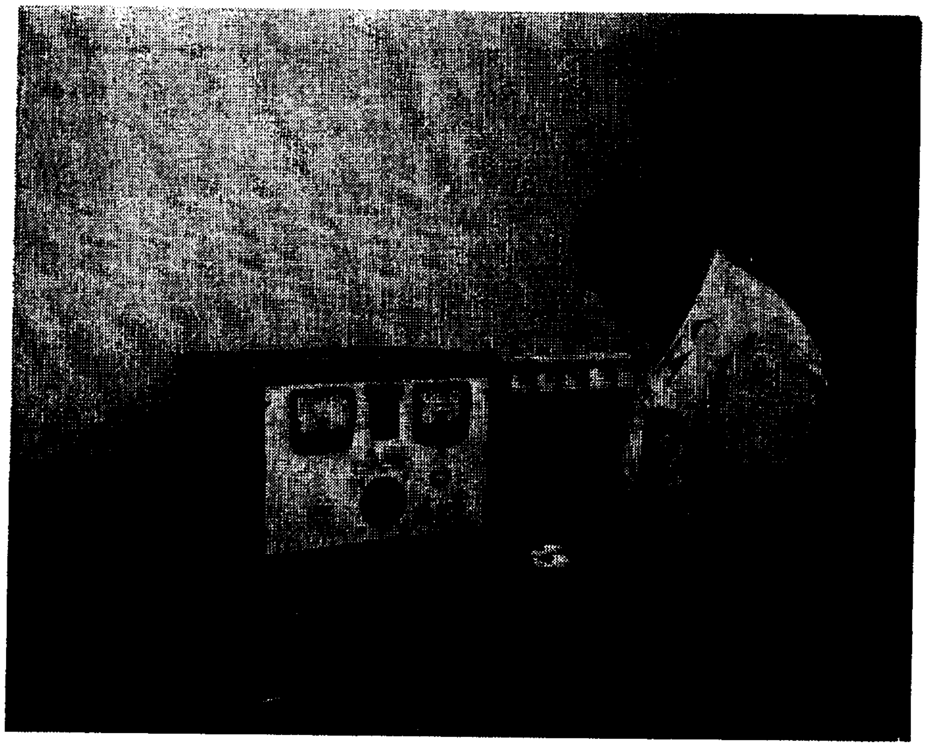


Figure 3-12. Selectron Plating of Aluminum (05145M)

3.2.3 EVALUATION. Evaluation of both the electroless nickel and Selectronic nickel plating has been completed. During testing, the electroless nickel plate was found to be superior to the Selectronic plating method; however, both processes may be used (depending upon the application).

A test was conducted whereby 1.3 cm (0.5 in.) thick 6061 aluminum tee sections were Con Braz joined using both electroless and Selectronic plated nickel. All specimens were baked at 450K (350F) for one hour after plating before Con Braz joining using a 95% cadmium - 5% silver alloy. Lengths of 2.5 cm (1 in.) from each section were tested in tension. The results, given in Table 3-2, show that the joints made with electroless plated nickel have greater cross-tension strength than those made with Selectronic plated nickel. Failure in all cases was by peeling of the nickel from the aluminum surface. Figure 3-13 shows failure surfaces of brazed 6061 aluminum specimens failed in tension when the nickel peeled from the surface.

To determine plating bond strength in shear, two 0.013 m (0.5 in.) thick 6061 aluminum specimens were electroless nickel plated and Con Braz joined. These specimens were tested in shear and failed at 82.8 MN/m^2 (12.0 ksi). The failure mode in both specimens was cohesive failure of the braze alloy with the nickel plating still adhering to the aluminum surfaces.

Table 3-2. Comparison of Tee Specimens Electroless and Selectronic Nickel Plated

Specimen No.		Strength MN/m^2	(ksi)
EC1		37.7	5.45
EC2		44.4	6.43
EC3		47.2	6.85
	Avg.	43.1	6.24
SEL1		38.9	5.64
SEL2		28.9	4.20
SEL3		35.3	5.13
	Avg.	34.5	5.00

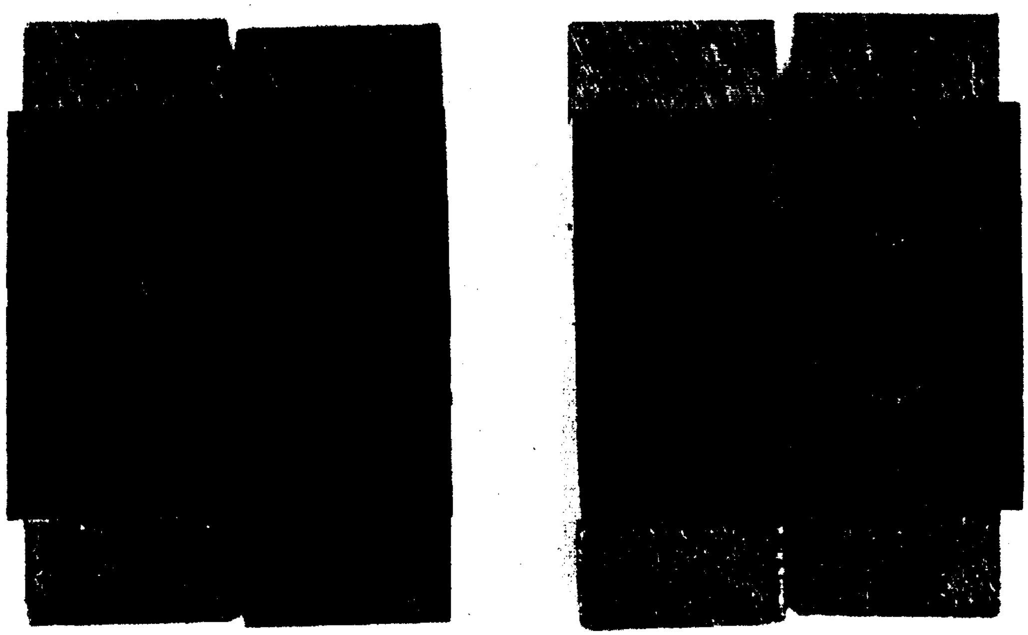


Figure 3-13. Failure Surfaces of Brazed, Nickel Plated Aluminum Tension Specimens. Failure Occurred by Peeling of the Nickel Plate (119425B)

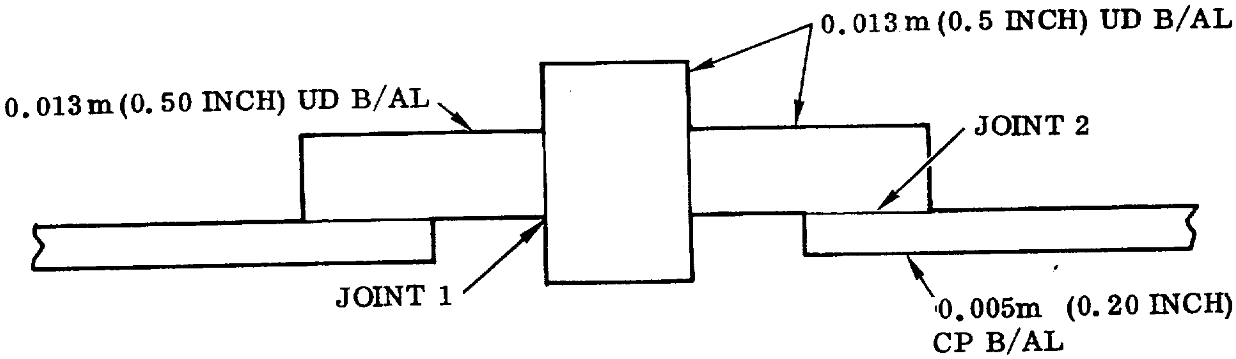
3.3 JOINING DEVELOPMENT

The objective of this phase of the program was to investigate various joining methods and select those to be used to fabricate the subcomponent and component assemblies. Several joining methods were developed and evaluated, and design data generated for each method. Selection of the joining methods used was on the basis of joint strength, ease of fabrication, and applicability to production of full-scale B/Al structural components. The candidate joining methods were the Con Braz technique, resistance spot welding, resistance spot joining, and mechanical fastening. The joints required for the subcomponent assemblies are shown in Figure 3-14 and are referred to by number. Schedules were developed and test coupons made from materials of thicknesses, orientation, and composition similar to those projected for subcomponent assemblies. This ensured the validity of the joint development test results. The B/Al for the joint development tests was ordered before final definition of the subcomponent assemblies; consequently, 0.23 cm (0.09 in.) and 0.43 cm (0.17 in.) thick material was used instead of the 0.25 cm (0.10 in.) and 0.5 cm (0.20 in.) thick material indicated in the joint configurations; 1.2 cm (0.5 in.) thick material was used where indicated. Only the most practical joining methods were considered for a particular joint. In all cases the joint tests were designed to simulate, as closely as possible, the actual loading conditions that were to be experienced in the subcomponent and component assemblies. Typical joint test specimens used in the development program are shown in Figure 3-15.

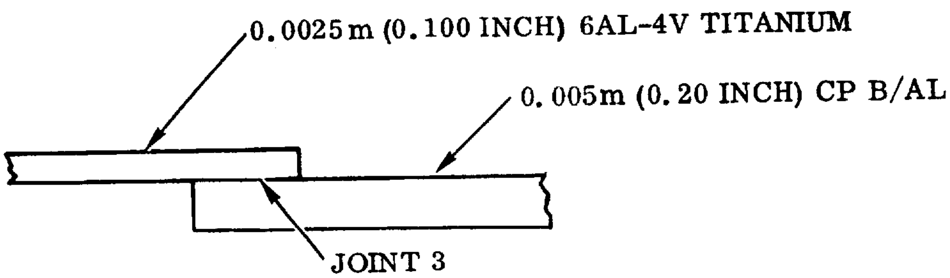
The specimen type for each joint test, the joining methods evaluated for each joint, the materials and material thicknesses, the number of test specimens, and the testing conditions are itemized in Table 3-3. All joint systems evaluated were tested at room temperature and 366K (200F); selected testing was conducted at 589K (600F).

3.3.1 <u>CON BRAZ JOINING</u>. This is a brazing process in which consolidated sheet material is assembled to a structural shape and brazed together by either low- or high-temperature brazing methods including dip brazing, furnace brazing, and torch brazing. Preplaced fillets can be used to increase the joint strength, if necessary. An example of this joining process is the 48-cm (19-inch) long Con Braz joined I-section with 1.1 mm (0.045 in.) thick unidirectional B/Al caps and a 1.1 mm (0.045 in.) thick 6Al-4V titanium web shown in Figure 3-16.

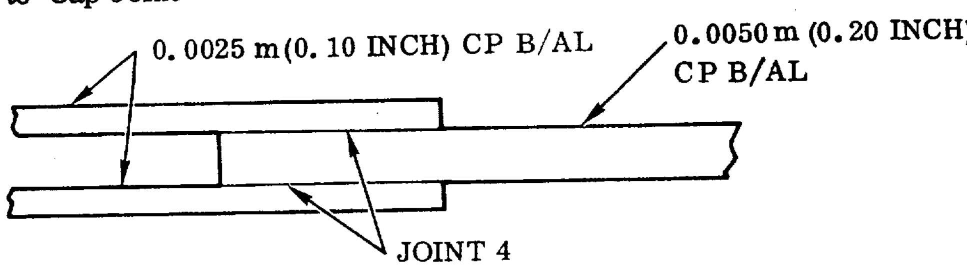
3.3.1.1 <u>Alloy Selection.</u> Several brazing alloys had been used to Con Braz join B/Al sections using radiant quartz lamps or an oxy-acetylene torch. Allstate 105, a 95% cadmium, 5% silver alloy, had the best elevated temperature properties of those used, but did not have sufficient strength at 589K (600F) to satisfy joint design requirements. Ney Metal Company's 380-1 braze alloy, a 95% zinc, 5% aluminum alloy, was evaluated as being potentially suitable for 589K (600F) service. Evaluation was conducted using single overlap shear specimens. The specimens used were 1 mm (0.040 inch) thick unidirectional B/Al joined to 3.2 mm (0.125 in.) thick 6061-T6 aluminum. (See Figure 3-17).



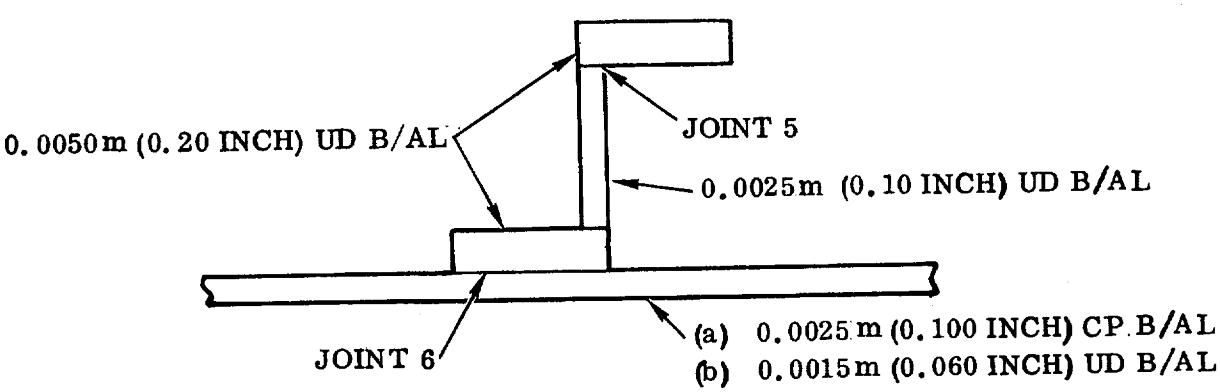
a. B/Al Web-to-Cap Joint



b. Titanium Web-to-Cap Joint

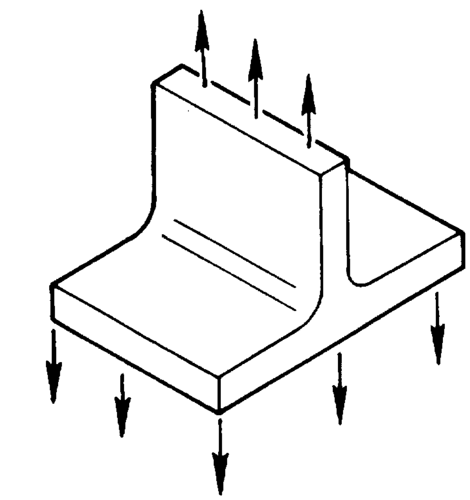


c. Web Splice

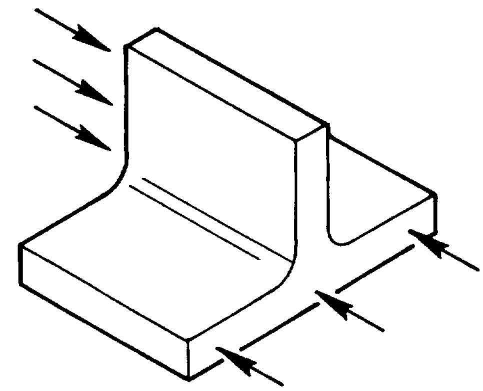


d. Stiffener and Stiffener/Web Joint

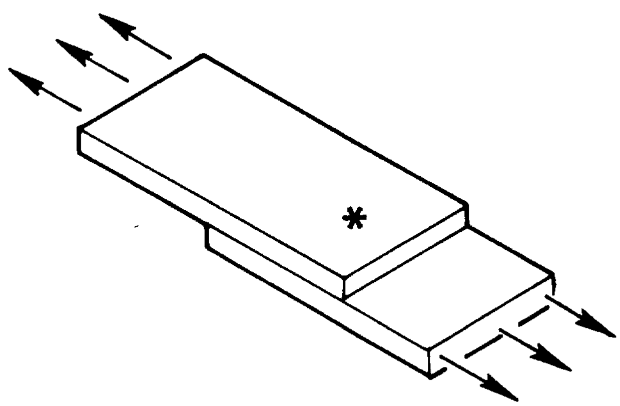
Figure 3-14. Joint Configurations Applicable to Fabrication of a Shear Web Beam



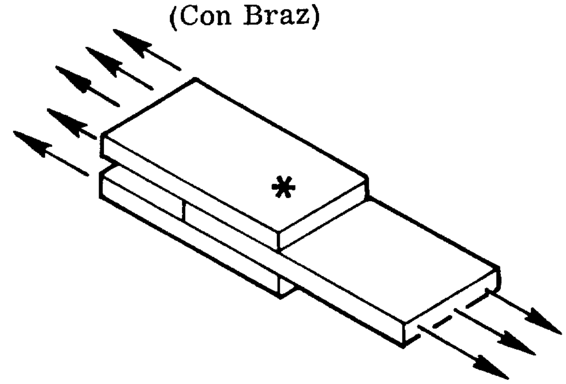
a. Tee Tension Specimen
(Con Braz)



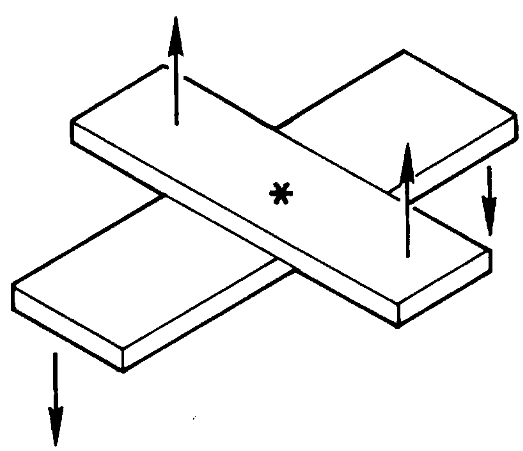
b. Tee Shear Specimen
(Con Braz)



c. Single Overlap Shear Specimen
(Spot Weld, Spot Join and
Fastener)



d. Double Overlap Shear Specimen
(Spot Weld and Fastener)



e. Cross Tension (Spot Weld)

Figure 3-15. Typical Joint Test Specimens

Table 3-3. Joint Development Test Program

Joint	Material	Test Specimen	Joining Method	Test Temperature RT	Test Temperature 366K (200F)	Test Temperature 589K (600F)
1-Cap Flange to Leg	0.013m UD B/Al	Tee Tension	Con Braz	X	X	
	0.013m UD B/Al	Tee Shear	Con Braz	X	X	
2-Cap Leg to Web	0.012m UD B/Al 0.0044m CP B/Al	Single Lap Shear	Res. Spot Weld	X	X	X
3-Cap Leg to Web	0.0044m CP B/Al 0.0015m Ti	Single Lap Shear	Mech. Fasteners	X	X	X
			Res. Spot Join	X	X	X
4-Web/Doubler Splice	0.0023m CP 0.0044m CP	Double Lap Shear	Mech. Fasteners	X	X	X
			Res. Spot Weld	X	X	
5-Stiffener Flange to Stiffener Web	0.004m UD B/Al	Tee Tension	Con Braz	X	X	
	0.004m UD B/Al	Tee Shear	Con Braz	X	X	
6-Stiffener Flange to Web	(a) 0.0025m CP B/Al 0.005m UD B/Al	Single Lap Shear	Res. Spot Weld	X		
	(b) 0.0015m UD B/Al 0.005m UD B/Al		Res. Spot Weld	X		

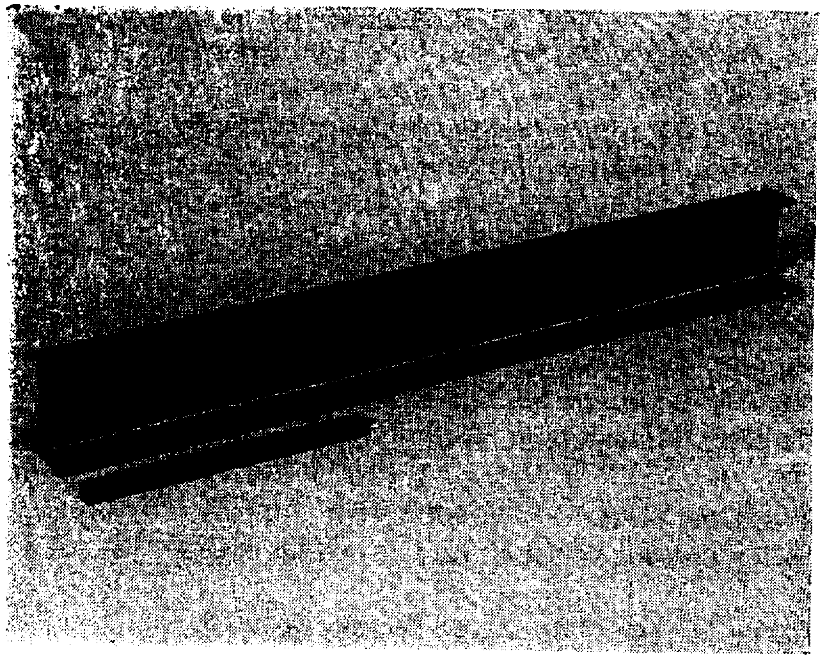


Figure 3-16. Con Braz Joined B/Al I-Section With a Titanium Web (118149B)

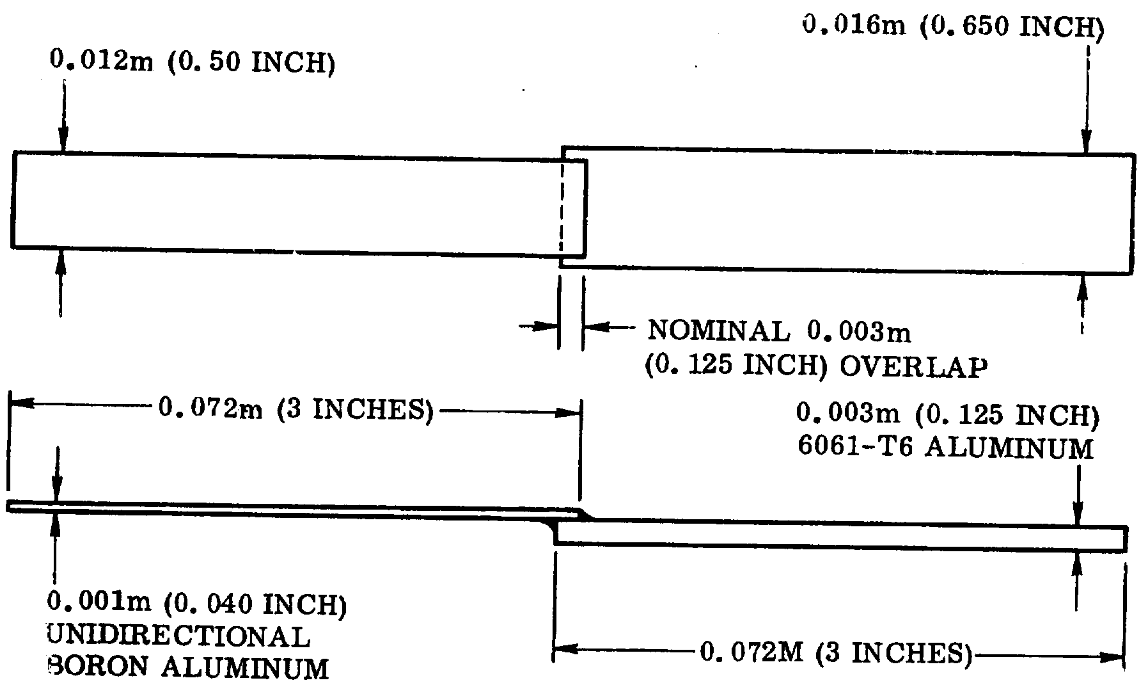


Figure 3-17. Single Overlap Shear Specimens

The joining technique used to make the overlap shear specimens was standard torch brazing. All specimen parts were cleaned and electroless nickel plated with a nominal thickness of 0.0005 mm (0.2 mil) per the procedure detailed in Specification 0-73541 Joining, Con Braz, Boron/Aluminum Composite, Specification for in Appendix A. This procedure prevents solution of the thin outer aluminum alloy layer of the composite. Actual joints were made by fluxing both surfaces to be joined with Ney Metal Company's 380 flux, clamping the overlapped parts in a stainless steel fixture for alignment, and heating with a soft, slightly carburizing, oxy-acetylene flame. Joint clearance was contact only, and a small piece of alloy was preplaced at one end of the joint. The joints were made through capillary action. Only the joint area and small adjacent areas were heated to or slightly above the flow point of the alloy. Flux removal was easily accomplished in hot water.

The results of room and elevated temperature shear tests of the parts made with the 95% Zn -5% Al alloy are compared in Table 3-4 with data for the 95% Cd-5% Ag alloy.

The 95% Zn -5% Al alloy has in excess of 276 MN/m^2 (4000 psi) shear strength at 589K (600F), which satisfies the design requirements for a B/Al structural joint intended to operate at that temperature. This is a significant improvement over the 56 MN/m^2 (825 psi) obtained at 589K (600F) with the 95% Cd-5% Ag alloy. The room temperature and 366K (200F) properties of the zinc-based alloy approximate those of the cadmium-based alloy.

The Allstate 105 alloy was selected for the lower temperature (366K) applications because it is easier to work with than the 380-1 and results in a cleaner joint. This is primarily due to the larger active temperature range of the vendor supplied flux for the 105 alloy (see Table 3-5).

3.3.1.2 Process Development. Con Braz joining was to have been used for the web-to-cap joint (B/Al to B/Al) and tension-field panel subcomponents at Joints 1 and 5. Room temperature and 366K (200F) Joint 1 and 5 tee specimens were Con Braz joined using Allstate 105 alloy. The test specimens had a 2.54 cm (1.0 in.) long joint length, and a gap of 0.1 mm (0.005 in.) was maintained during joining.

An existing fixture was used in a 120,000-pound capacity Tinius Olsen Universal Testing machine for tension testing T-sections. Figure 3-18 shows the fixture being used to test a 3.1 mm (0.125 in.) thick aluminum specimen. The T-section has a 0.043m (1-3/4 in.) stem to allow sufficient gripping length to obtain a uniform grip on the stem.

A T shear fixture was also designed and fabricated, (Figure 3-19). This fixture was made from cold-rolled steel and has hardened steel inserts at the bearing surfaces to prevent damage by the exposed boron filaments. The fixture was designed to test 12.7mm (0.5 in.) thick material but can be used for testing any thinner gage tee section.

Table 3-4. Lap Shear Tests With 95% Cadmium, 5% Silver (105) and 95% Zinc, 5% Aluminum (380) Braze Alloys

Test Number	Test Temperature K	Test Temperature F	Strength MN/m^2	Strength ksi	Failure* Mode
105-A	RT		826	12.0	1
105-B	RT		697	10.1	1
105-C	RT		894	13.0	1
			805	11.7 Avg	
105-D	366	200	802	11.6	1
105-E	366	200	1020	14.8	1 and 2
105-F	366	200	844	12.2	1
			889	12.9 Avg	
105-G	422	300	578	8.4	
105-H	422	300	867	12.6	1
105-I	422	300	659	9.6	1
			701	10.2 Avg	
105-J	589	600	91	1.3	2
105-K	589	600	21	0.3	2
			56	0.8 Avg	
380-A	RT		1017	14.8	2
380-B	RT		617	9.0	1
380-C	RT		766	11.1	1
			804	11.6 Avg	
380-D	366	200	869	12.6	2
380-E	366	200	1020	14.8	2
380-F	366	200	924	13.4	2
			938	13.6 Avg	
380-G	589	600	260	3.8	2
380-H	589	600	302	4.4	2
380-I	589	600	354	5.2	2
			305	4.5 Avg	

Note: RT, 422K (300F) and 589K (600F) data for 95% Cadmium, 5% Silver alloy was obtained from Reference 7.

* Failure Mode
1 = Interlaminar shear failure of composite.
2 = Adhesive and cohesive failure of braze alloy.

Table 3-5. Comparison of 95% Cadmium-5% Silver and 95% Zinc-5% Aluminum Braze Alloy Systems

	95% Zn 5% Al	95% Cd 5% Ag
Commercial Alloy	Ney Metal Co. 380-1	Allstate 105
Solidus	656K (720F)	630K (675F)
Liquidus	(Eutectic alloy)	672K (750F)
Recommended Flux	Ney Metal Co. 380	Allstate 105
Active Temperature Range of Flux	645K to 662K (700F to 730F)	560K to 700K (550F to 800F)

Both 0.013m (0.5 in.) thick and 0.004m (0.17 in.) thick B/Al T-sections were successfully tested at both room temperature and 366K (200F) using the fixture.

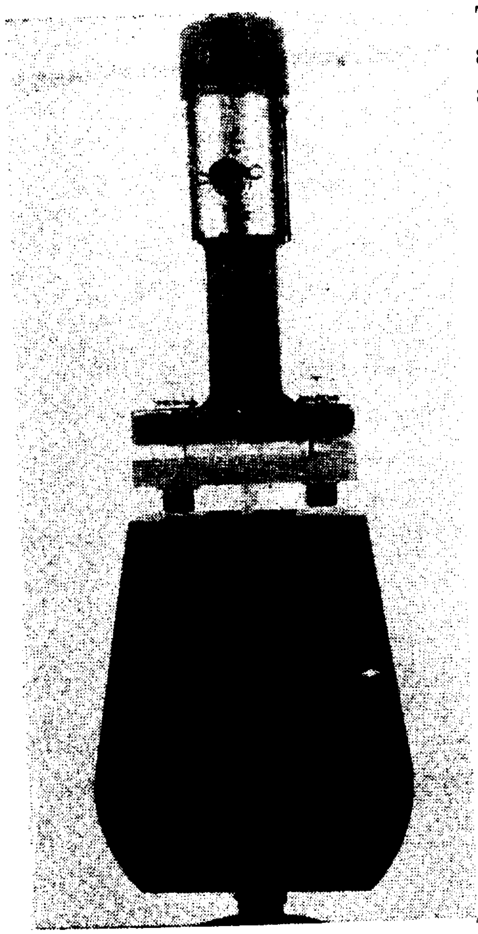


Figure 3-18. Tee Tension Test Fixture (117856B)

The results of both tension and shear tests of Joint 1 and 5 specimens at room temperature and 366K (200F) are given in Table 3-6.

During both the tension and shear tests of Joint 1 specimens, it was found that boron filaments had pulled out of the surface of the leg of the T-section even in those areas that appeared to be well brazed. This is attributed to filament damage during the sawing, which chips the boron filaments and thus disrupts the bond between the boron filament and the aluminum matrix. This damage was evident even before Con Braz joining the parts. Attempts to remove the loose boron filaments by glass-bead peening the cut edges prior to nickel plating were unsatisfactory. Although, during brazing, the flux and braze alloy appeared to flow uniformly across the joints, examination of Joint 1 specimen failure surfaces showed that only about 50% of the joint areas were brazed. Flux entrapment was evident in the remaining areas. The unbrazed areas were generally in the center of the joint where the braze alloy had sporadically flowed across the joint and then formed a continuous fillet at the other side, entrapping the flux. This only occurred with the 0.013m (0.5 in.) thick Joint 1 material and accounts for the low test values obtained with these specimens. Further Con Braz joining tests were conducted using 0.013m (0.5 in.) thick B/Al by varying the brazing gap between

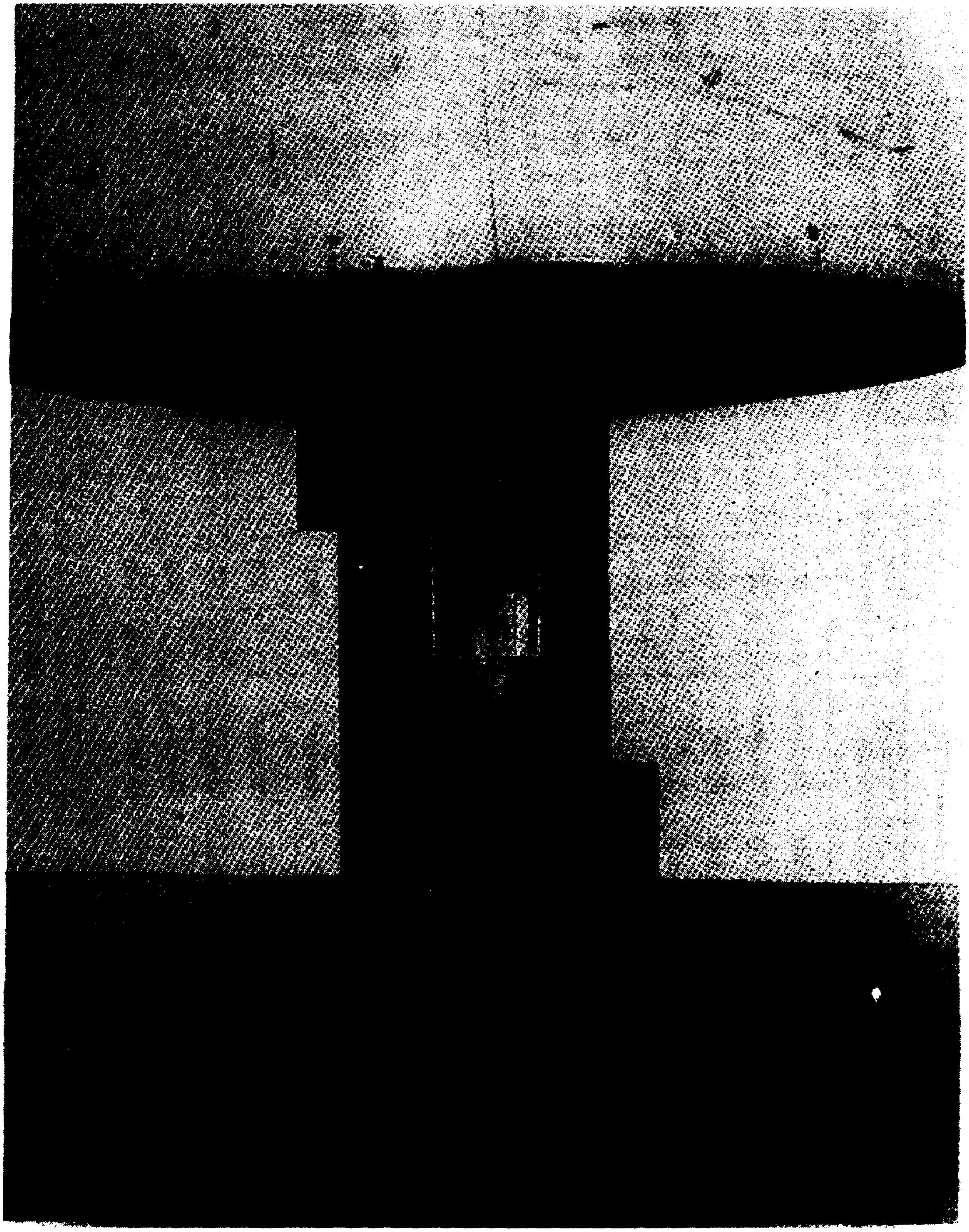


Figure 3-19. Tee Shear Test Fixture (122451B)

Table 3-6. Con Braz Joined Tee Section Tension and Shear Test Results

Joint and Test Number	Material (B/Al)	Type of Test	Test Temperature K	Failure Load		Failure Stress	
				N	(lb)	MN/m^2	(psi)
1F-1	13mm UD to 13mm UD	Tension	RT	1,980	440	6	900
1F-2	13mm UD to 13mm UD	Tension	RT	922	205	3	420
1F-3	13mm UD to 13mm UD	Shear	RT	13,500	3,000	42	6,130
1F-4	13mm UD to 13mm UD	Shear	RT	11,700	2,610	37	5,320
1F-5	13mm UD to 13mm UD	Shear	RT	15,200	3,375	47	6,880
1F-6	13mm UD to 13mm UD	Shear	366	13,180	2,960	42	6,060
1F-7	13mm UD to 13mm UD	Shear	366	6,550	1,470	21	3,100
5F-1	4mm UD to 4mm UD	Tension	RT	3,900	868	41	5,925
5F-2	4mm UD to 4mm UD	Tension	RT	3,600	804	37	5,475
5F-3	4mm UD to 4mm UD	Shear	RT	8,300	1,860	71	10,330
5F-4	4mm UD to 4mm UD	Shear	RT	9,600	2,130	73	10,650
5F-5	4mm UD to 4mm UD	Shear	RT	9,700	2,157	74	10,780
5F-6	4mm UD to 4mm UD	Tension	366	3,740	840	38	5,500
5F-7	4mm UD to 4mm UD	Shear	366	8,000	1,798	81	11,900
5F-8	4mm UD to 4mm UD	Shear	366	6,300	1,430	62	9,000
5F-9	4mm UD to 4mm UD	Shear	366	9,050	2,034	82	11,940

0.005mm (0.002 in.) and 0.3mm (0.01 in.). No increase in the joint strength or brazed area of the joint was observed. To encourage better flow of the braze alloy and wetting of the nickel-plated surfaces some specimens were Selectron silver-plated prior to brazing. The results were no better than those previously obtained. The use of preplaced braze alloy foil was also evaluated and found to offer no improvement. Joint 1 specimens were also brazed using Eutectic 157 braze alloy, a 95% tin, 5% silver alloy with a melting point of 491K (425F). This alloy has considerably better wetting and flow characteristics than the Allstate 105 alloy. The joint surfaces were electroless nickel-plated and Selectron tin-plated prior to brazing. Shear strengths of 25 MN/m^2 (3.67 ksi) and 32 MN/m^2 (4.74 ksi) were obtained and only 50% of the joint area was brazed; these values are lower than those reported in Table 3-6 with the Allstate 105 alloy.

It was concluded that the strength values presently attainable with the Con Braz joined 0.013m (0.5 in.) T-sections did not satisfy the design requirements for the shear resistant beam. It was felt that adequate joint strengths could be developed, but this would require refinement of techniques beyond the scope of the present program.

The room temperature test results obtained with the 0.004m (0.15 in.) Joint 5 T-specimens exceeded the design requirements; therefore, the component I-beams (see Volume I) were Con Braz joined as originally intended. The results also indicated there was no loss in strength at 366K (200F). Examination of the failed Joint 5 specimens showed that they were 80 to 90% brazed.

3.3.2 RESISTANCE WELDING. Resistance welding melts the aluminum matrix without damaging the filaments. The weld nugget forms around the filaments, and a high joint efficiency is attainable. Resistance welding does not cut filaments, as is the case with mechanical fasteners, nor are filaments destroyed as in fusion welding. Resistance welding is economical and can produce structurally strong lap joints.

Resistance spot welding was considered for Joints 2, 4, 6a, and 6b of the shear beam and for joining the unidirectional B/Al hats to the crossply B/Al skin of the compression panel (see Volume I and Section 4). This required developing five resistance spot welding schedules:

a. Schedule RW1: 0.013m (0.5 in.) unidirectional B/Al to 0.0044m (0.17 in.) crossply B/Al.

b. Schedule RW2: 0.0023m (0.09 in.) crossply B/Al to 0.0044m (0.17 in.) crossply B/Al to 0.0023m (0.09 in.) crossply B/Al.

c. Schedule RW3: 0.005m (0.200 in.) unidirectional B/Al to 0.0015m (0.060 in.) unidirectional B/Al.

d. Schedule RW4: 0.005m (0.200 in.) unidirectional B/Al to 0.0025m (0.100 in.) crossply B/Al.

e. Schedule RW5: 0.0025m (0.10 in.) unidirectional B/Al to 0.0018m (0.07 in.) crossply B/Al.

The shear strength of the specimens made using schedules RW1 through RW4 are given in Table 3-7.

The schedule RW1 specimens all failed in shear with room temperature and 366K (200F) values of about 23,000 Newtons (5100 lb). A loss in strength of approximately 50% was noted in the 589K (600F) specimens.

The schedule RW2 specimens failed with a mixture of shear and tension modes. Figure 3-20 shows these failure modes. Room temperature and 366K (200F) strengths are between 21,600 Newtons and 28,400 Newtons (4900 lb and 6400 lb).

The schedule RW3 and RW4 specimens failed in shear at values of about 16,000 Newtons (3600 lb). All joint strengths adequately satisfied the design requirements for the relevant structures that are discussed in Volume I and Section 4.

Following the development of schedule RW1, assembly of the three web-to-cap (B/Al to B/Al) subcomponents was initiated. The joints obtained were inconsistent, and generally of poor quality; consequently, this spot-weld joint was eliminated in favor of titanium mechanical fasteners.

The 0.25 cm (0.1 in.) thick UD B/Al for schedule RW5 was fabricated by the Con Clad process (Section 4).

A schedule was developed that produced sound welds in joints between 0.25 cm (0.100 in.) UD B/Al that had been fabricated by the Con Clad process and 0.18 cm (0.070 in.) CP B/Al. Initial weld development was performed on standard 0.25 cm (0.100 in.) UD to 0.18 cm (0.070 in.) CP B/Al. This schedule, Table 3-8, had to be modified by increasing the weld heat input in order to weld the Con Clad composite. Heat is conducted away from the interface due to the additional Al on the Con Clad material surface.

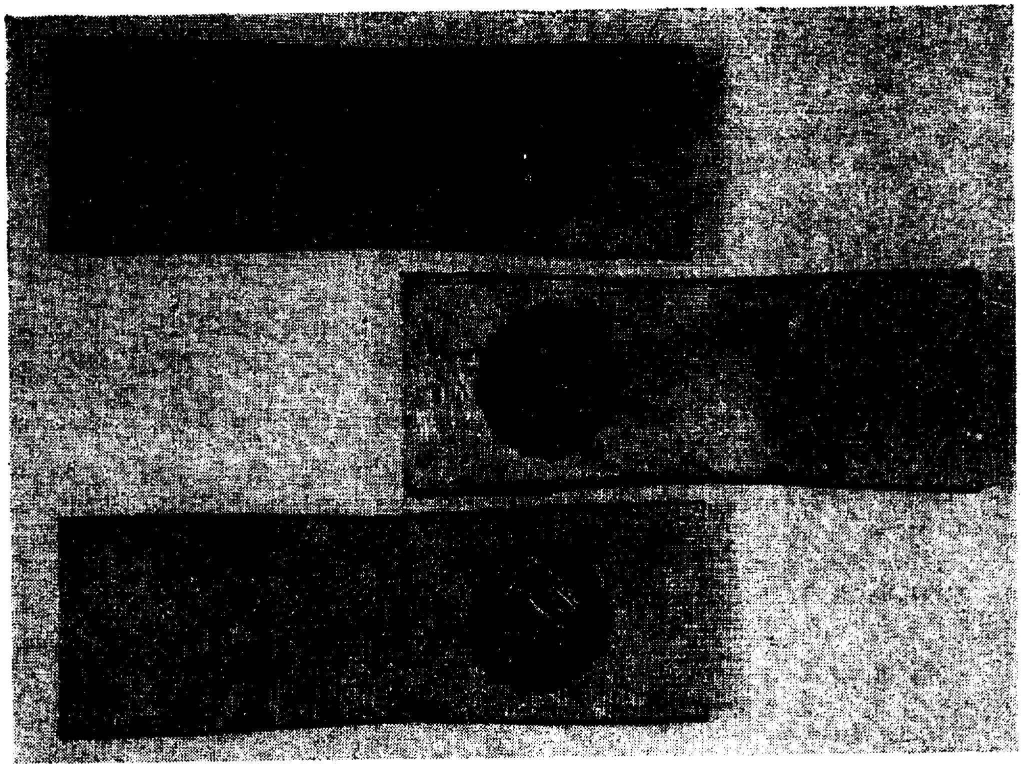
Lap shear tests were made at ambient temperature during weld development. All of the single spot joints were approximately 1.1 cm (0.44 in.) in diameter and failed in shear at approximately 12,240 N (2750 lb). Raising the weld heat input so that the diameter exceeded 1.3 cm (0.500 in.) changed the failure mode to net tension in the 0.18 cm (0.070 in.) composite, but also produced excessive deformation and filament damage. The cross tension and lap shear strength of the weld joints at 589K (600F) were structurally sufficient for the compression panel design loads. The 589K (600F) test results are included as Table 3-9.

Although previous work (Reference 7) has shown that post weld heat treatment increases the joint strength, this was not used because it would be impractical to heat treat full-size space shuttle structures, such as the shear resistant beam or compression panel, after assembly.

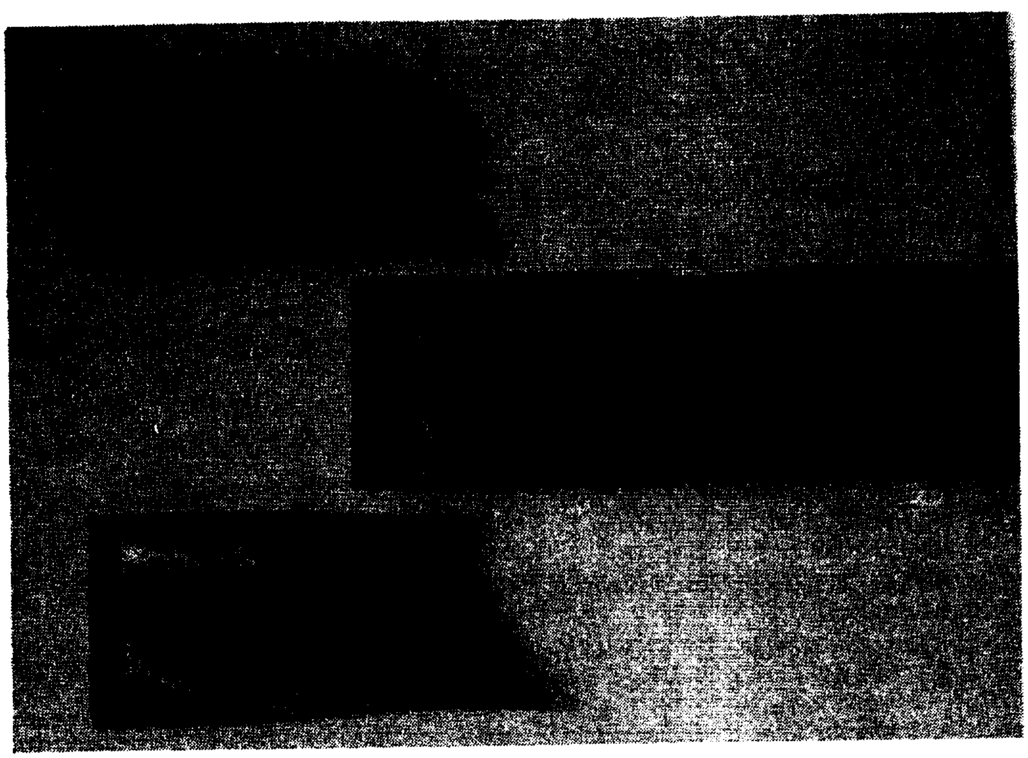
Table 3-7. Resistance Spot Welded Lap Shear Test Results

Test Number	Material	Type of Test Specimen	Test Temperature K	Test Temperature F	Failure Load Newtons	Failure Load lb	Failure Mode and Comments
2d-1	0.013 m UD B/Al to 0.0044 m CP B/Al	Single lap Shear	RT		23,300	5230	Shear
2d-2	0.013 m UD B/Al to 0.0044 m CP B/Al	Single lap Shear	RT		24,300	5470	Shear
2d-3	0.013 m UD B/Al to 0.0044 m CP B/Al	Single lap Shear	RT		21,700	4870	Shear
					23,100	5200	Average
2d-4	0.013 m UD B/Al to 0.0044 m CP B/Al	Single lap Shear	366	200	26,200	5690	Shear
2d-5	0.013 m UD B/Al to 0.0044 m CP B/Al	Single lap Shear	366	200	20,400	4590	Shear
					23,300	5100	Average
2d-6	0.013 m UD B/Al to 0.0044 m CP B/Al	Single lap Shear	589	600	12,600	2760	Shear
2d-7	0.013 m UD B/Al to 0.0044 m CP B/Al	Single lap Shear	589	600	10,900	2450	Shear
					11,700	2600	Average
4d-1	0.0023 m CP B/Al to 0.0044 m CP B/Al to 0.0023 m CP B/Al	Double lap Shear	RT		26,400	5950	Composite tension failure
4d-2	0.0023 m CP B/Al to 0.0044 m CP B/Al to 0.0023 m CP B/Al	Double lap Shear	RT		18,800*	4230	Tension and shear
4d-3	0.0023 m CP B/Al to 0.0044 m CP B/Al to 0.0023 m CP B/Al	Double lap Shear	RT		28,400	6410	Tension and shear
					27,400	6200	Average
4d-4	0.0023 m CP B/Al to 0.0044 m CP B/Al to 0.0023 m CP B/Al	Double lap Shear	366	200	21,600	4880	Tension and shear
4d-5	0.0023 m CP B/Al to 0.0044 m CP B/Al to 0.0023 m CP B/Al	Double lap Shear	366	200	27,000	6090	Shear
					24,300	5500	Average
6a-1	0.0025 m CP B/Al to 0.005 m UD B/Al	Single lap Shear	RT		16,200	3600	Shear
6a-2	0.0025 m CP B/Al to 0.005 m UD B/Al	Single lap Shear	RT		15,500	3450	Shear
					15,800	3500	Average
6b-1	0.0015 m UD B/Al to 0.005 UD B/Al	Single lap Shear	RT		18,900	4200	Shear
6b-2	0.0015 m UD B/Al to 0.005 UD B/Al	Single Lap Shear	RT		16,000	3560	Shear
6b-3	0.0015 m UD B/Al to 0.005 UD B/Al	Single Lap Shear	RT		13,000	2900	Shear
					16,000	3600	Average

* Severe expulsion occurred during welding and X-ray indicated a substandard weld.



(a) Shear Failure (119427B)



(b) Tension Failure (119426B)

Figure 3-20. Failed Resistance Spot Welded Specimens

Table 3-8. RW5 Weld Schedule

Top Sheet:	0.100 inch UD B/Al (with or without Con Clad coating*)
Bottom Sheet:	0.070 inch UD or CP B/Al*
Machine:	100 KVA, a-c, 3 phase, rocker arm
Top Electrode:	Class I, 5/8" diameter, full face with 8" spherical tip radius
Bottom Electrode:	Class I, 5/8" diameter, full face with 6" spherical tip radius
Weld Impulse:	8 cycles of heat and 5.5 cycles of cool
Pressure:	1000 lbs. weld, 2000 lbs. forge
Forge Delay:	0.4 cycles after end of weld
Preheat:	4 impulses of 36 percent phase shift
Weld heat:	8 impulses of 56 to 62* percent phase shift
Post heat:	4 impulses of 36 percent phase shift

*0.100 UD to 0.070 UD: 56 percent phase shift
0.100 UD Con Clad to 0.070 UD: 62 percent phase shift
0.100 UD Con Clad to 0.070 CP: 62 percent phase shift
Note: For Clarity, only English Units shown.

3.3.3 RESISTANCE JOINING. Joint 3 was originally planned to be made by resistance spot brazing, a process that involves nickel and copper plating both the B/Al and titanium surfaces prior to joining. Resistance joining is a process similar to resistance spot brazing in that it utilizes standard resistance welding equipment to heat the B/Al interface to a temperature above the melting point of aluminum but well below the melting point of titanium. Resistance joining replaced resistance spot brazing for the joint specimen fabrication, subcomponent and component assembly. The resistance joining process is a more convenient and economical process because it eliminates the requirement to plate either the B/Al or titanium prior to joining. This decision to use resistance joining was based on tests that showed that resistance joining produced joints with strengths equivalent to, or greater than those obtained with resistance spot brazing.

The results of the resistance joining test are shown in Table 3-10. Each joint consisted of two spots approximately 1.65 cm (0.65 in.) in diameter overlapped by 0.38 cm (0.15 in.). In all cases, failure was by shear in the B/Al. Figure 3-21 shows the failure surfaces of a specimen tested at 589K (600F) and clearly illustrates the two overlapped spots and the failure mode. The extensive necking seen in this specimen was typical of those tested at 589K (600F). The strengths obtained adequately satisfy the requirements for a joint of this type and indicate that there is no loss in strength at 366K (200F) and only a 30% loss in strength at 589K (600F).

Table 3-9. 589K (600F) Resistance Spot Weld Mechanical Properties

Spec.	0.100 in.* B/Al	0.070 in. B/Al	Test		Average Dia. (in)	Failure Load (lb)	Shear Stress (ksi)	Comments
C1-1	UD	UD	LS		0.43	> 1790	-	Grip Slippage
C1-2	UD	UD	LS		0.43	2110	14.6	
C1-3	UD	UD	LS		0.42	2057	14.9	
				Avg.	0.43	2084	14.7	
C9-1	UDCC	UD	LS		0.45	2215	13.9	
C9-2	UDCC	UD	LS		0.41	1775	13.4	
C9-3	UDCC	UD	LS		0.43	2200	15.2	
				Avg.	0.43	2063	14.2	
C8-1	UDCC	CP	LS		0.39	1460	12.3	
C8-2	UDCC	CP	LS		-	-	-	Test Failure
C8-3	UDCC	CP	LS		0.39	1480	12.5	
				Avg.	0.39	1470	12.4	
C7-1	UDCC	UD	2LS		0.41	3133	11.9	
C4-1	UDNC	UD	2LS		-	-	-	
							Tension Stress (ksi)	
B2-1	UDCE	CP	CT		0.32	189	2.3	Poor Weld Schedule
B2-2	UDCE	CP	CT		0.36	298	3.0	
B2-3	UDCE	CP	CT		0.39	410	3.1	
B2-4	UDCE	CP	CT		0.38	359	3.2	
				Avg.	0.36	314	2.9	
C6-1	UDCC	CP	CT		0.41	461	3.5	
C6-2	UDCC	CP	CT		0.43	566	3.9	
C8-1	UDCC	CP	CT		0.44	537	3.5	
C8-2	UDCC	CP	CT		0.42	516	3.8	
				Avg.	0.42	520	3.7	

Note: For clarity, only English Units are shown.

*UD = Unidirectionally reinforced, CC = Con Clad, CP = Cross Ply reinforced, NC = Con Clad without the clad coating, CE = Con Clad from edge of panel, LS = Lap Shear, 2LS = 2 spot Lap Shear, CT = Cross tension

Table 3-10. Resistance Spot Joined Single Lap Shear Test Results (0.0045 m CP B/Al to 0.0015 m 6 Al-4V Titanium)

Test Number	Test Temperature K	(F)	Failure Load Newtons	(lb)	Failure Mode
3g-1	RT	—	12,850	2880	Shear in composite
3g-2	RT	—	15,800	3470	Shear in composite
			14,300	3200 Avg	
3g-3	366	200	16,500	3720	Shear in composite
3g-4	366	200	15,650	3455	Shear in composite
			16,100	3600 Avg	
3g-5	589	600	11,500	2580	Shear in composite
3g-6	589	600	12,050	2703	Shear in composite
			11,700	2600 Avg	

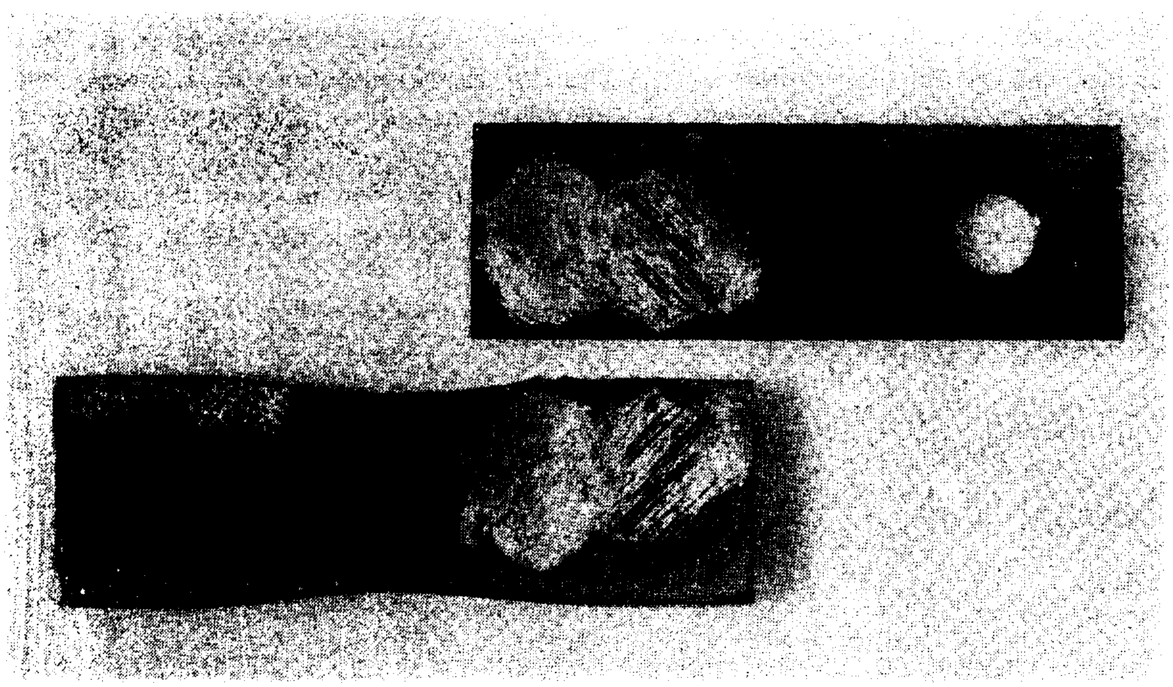


Figure 3-21. Shear Failure in Resistance Joined Titanium to B/Al Specimen (120163B)

3.3.4 MECHANICAL FASTENERS. Mechanical fasteners can be applied with minimum risk if the weight penalty is tolerable. In general, the lap shear strength of mechanically fastened joints is lower than resistance spot weld joints (Reference 7).

Titanium hi-shear mechanical fasteners were considered for Joints 3 and 4. The design philosophy was to preclude shearout, bearing and fastener shear failure, and to cause a net tension failure. With Joint 3, failure was intended to occur in the composite. The specimens were 0.028m (1.12 in.) wide with a fastener edge distance of 0.025m (1 in.). The single lap shear specimens had a 0.075m (3 in.) overlap with two fasteners on 0.025m (1 in.) centers, and the double lap shear specimens had a 0.050m (2 in.) overlap with one fastener in the center. Hi-shear titanium fasteners, 0.0063m (0.25 in.) diameter, were used.

The results of these tests at room temperature, 366K (200F) and 589K (600F) are given in Table 3-11. The Joint 3 results indicate a 25% loss in strength at 366K (200F) and a 50% loss in strength at 589K (600F). The Joint 4 results show no similar loss in strength at 366K (200F) but do indicate a 50% loss in strength at 589K (600F). These joints meet all design requirements.

3.4 COMPOSITE FORMING

A new forming technique, Con Clad forming, was developed on a company-funded program (Reference 24) and used on this program to fabricate B/Al hat-sections. The technique involves the use of steel cladding on the surfaces of the composite material. By using proper thicknesses of steel, the effective transverse strength of the composite (during forming) is increased, and the neutral axis of the workpiece is shifted in such a manner that the composite, during forming, is predominantly in compression. These two factors permit room temperature forming of B/Al composite structures.

Table 3-11. Mechanical Fastener Lap Shear Test Results

Test Number	Material	Type of Test Specimen	Test Temperature K	Test Temperature (F)	Failure Load Newtons	Failure Load (lb)	Maximum Tension Stress MN/m^2	Maximum Tension Stress (ksi)	Failure Mode and Comments
3a-1	0.0044m CP B/Al to 0.0015m 6Al-4V titanium	Single Lap Shear	RT		14,100	3170	146	21.2	Net tension - test conditions caused premature failure
3a-2	0.0044m CP B/Al to 0.0015 m 6Al-4V titanium	Single Lap Shear	RT		26,000	5860	270	39.1	Net tension and interlaminar shear
3a-3	0.0044m CP B/Al to 0.0015m 6Al-4V titanium	Single Lap Shear	RT		26,500	5980	275	39.9	Net tension and interlaminar shear
					26,250	5020			Average
3a-4	0.0044m CP B/Al to 0.0015m 6Al-4V titanium	Single Lap Shear	366	200	17,300	3875	178	25.8	Net tension
3a-5	0.0044m CP B/Al to 0.0015m 6Al-4V titanium	Single Lap Shear	366	200	21,800	4920	226	32.8	Net tension and interlaminar shear
					19,550	4400			Average
3a-6	0.0044m CP B/Al to 0.0015m 6Al-4V titanium	Single Lap Shear	589	600	12,200	2716	126	18.2	Net tension and interlaminar shear
3a-7	0.0044m CP B/Al to 0.0015m 6Al-4V titanium	Single Lap Shear	589	600	12,000	2690	123	17.9	Net tension and interlaminar shear
					12,100	2700			Average
4a-1	0.0023m CP B/Al to 0.0044m CP B/Al to 0.0023m CP B/Al	Double Lap Shear	RT		27,800	6260	288	41.7	Net Tension
4a-2	0.0023m CP B/Al to 0.0044m CP B/Al to 0.0023m CP B/Al	Double Lap Shear	RT		26,600	6010	276	40.0	Net Tension
4a-3	0.0023m CP B/Al to 0.0044m CP B/Al to 0.0023m CP B/Al	Double Lap Shear	RT		27,900	6300	290	42.0	Net Tension
					27,420	6180			Average
4a-4	0.0023m CP B/Al to 0.0044m CP B/Al to 0.0023m CP B/Al	Double Lap Shear	366	200	25,900	5830	268	38.9	Net Tension
4a-5	0.0023m CP B/Al to 0.0044m CP B/Al to 0.0023m CP B/Al	Double Lap Shear	366	200	26,600	6000	276	40.0	Net Tension
					26,250	5915			Average
4a-6	0.0023m CP B/Al to 0.0044m CP B/Al to 0.0023m CP B/Al	Double Lap Shear	589	600	11,800	2650	122	17.7	Net Tension
4a-7	0.0023m CP B/Al to 0.0044m CP B/Al to 0.0023m CP B/Al	Double Lap Shear	589	600	12,000	2920	135	19.5	Net Tension
					11,900	2775			Average

SECTION 4

COMPONENT FABRICATION

The primary objective of this program was to demonstrate the applicability of B/Al structures for space shuttle. In meeting this objective, it was necessary to develop manufacturing procedures capable of handling thick, large-scale B/Al structures. After developing these procedures, it was then necessary to select and build representative hardware to demonstrate the fabricability of B/Al. The following structures were fabricated: 1) a 1.0×0.96m (40×38 in.) shear beam utilizing 0.55m (0.21 in.) thick $\pm 45°$ heat-treated web sections spliced together in the center of the panel by resistance welding, 22 I-section stiffeners consisting of 0.17 cm to 0.28 cm (0.068 in. to 0.109 in.) thick unidirectional B/Al plates Con Braz joined and attached to the web by resistance welding, and one unidirectional B/Al compression cap tapered in thickness from 1.7 cm (0.64 in.) to 1.2 cm (0.44 in.) along its 1.27m (50 in.) length; and 2) a 2.03×0.74m (80×29 in.) uniformly loaded compression panel consisting of five unidirectional hat sections, 0.25 cm (0.1 in.) thick and 2.03m (80 in.) long, resistance welded to a 0.18 cm (0.070 in.) thick $0 \pm 45°$ crossply B/Al skin.

4.1 SHEAR BEAM COMPONENT

Prior to fabricating the shear beam component various subcomponents were designed and fabricated to evaluate the techniques under consideration for joining elements of the shear beam and to verify design assumptions and predicted strengths.

4.1.1 <u>SUBCOMPONENT TEST SPECIMENS</u>. Three types of subcomponents were fabricated along with their steel test fixtures. These are listed below and discussed briefly. Further details and photographs of the subcomponents and their test fixtures are given in Volume I.

a. Web splice — Four web splice subcomponent specimens were fabricated. Two consisted of B/Al joined to B/Al using titanium mechanical fasteners and two consisted of B/Al joined to B/Al by resistance spot welding. One mechanically fastened and one resistance spot welded subcomponent were thermally cycled 100 times between 366K (200F) and 77K (-320F) before assembly in the test fixture.

b. Tension field panels — Two tension field specimens, in which Con Braz joined Z-section B/Al stiffeners were resistance spot welded to a B/Al web were fabricated. The web for one specimen was 0.254 cm (0.1 in.) thick $\pm 45°$ crossply B/Al and for the other 0.152 cm (0.06 in.) unidirectional B/Al.

c. Web-to-cap joint — Three web-to-cap joint subcomponent specimens were fabricated. For these specimens, B/Al was resistance spot joined to 6Al-4V titanium. One of the specimens was thermally cycled 100 times between 366K (200F) and 77K (-320F) before assembly into the test fixture.

All subcomponent specimens were tested to failure. The results are analyzed in detail in Volume I. The failure loads for the specimens are given in Table 4-1. It was concluded that thermally cycling the parts 100 times between 366K (200F) and 77K (-320F) was not detremental to the joints, and that the joint design concepts proposed for the full-scale component were valid.

Table 4-1. Subcomponent Test Results

Specimen I.D.	Joining Method	Failure Load kN	Failure Load lb
Web splice	Resistance welded	100.1	22,500
Web splice	Resistance welded	115.6*	26,000
Web splice	Mechanically fastened	232.6	52,300
Web splice	Mechanically fastened	239.3*	53,800
Web-to-cap	Resistance joined	114.3	25,700
Web-to-cap	Resistance joined	127.0*	28,550
Web-to-cap	Resistance joined	151.2	34,000
Tension field (UD web)	Con Braz/resistance welded	317.6	71,400
Tension field (Crossply web)	Con Braz/resistance welded	369.2	83,000

*Thermally cycled 100 times between 366K (200F) and 77K (-320F) prior to testing.

4.1.2 COMPONENT FABRICATION. A 1.0 × 0.96m (40 × 38 in.) B/Al shear beam component test specimen was fabricated to demonstrate production methods and design concepts developed on the program. The detailed designs and proposed test plan for the structure are described in Volume I. A sketch of the shear beam component is shown in Figure 4-1. The fabrication of the beam is described in the following sections.

4.1.2.1 Stringer Fabrication. Twenty-one B/Al vertical I-section stiffeners and one B/Al horizontal I-section stiffener were fabricated for the shear beam component. All vertical stiffeners with the exception of the two adjacent to the web splice possess the same cross-sectional configuration and were made from 0.17 cm (0.068 in.) thick unidirectional B/Al. The two vertical stiffeners at the splice area have a bottom cap made from 0.28 cm (0.109 in.) thick ±45° crossply B/Al that is 11.4 cm (4.50 in.)

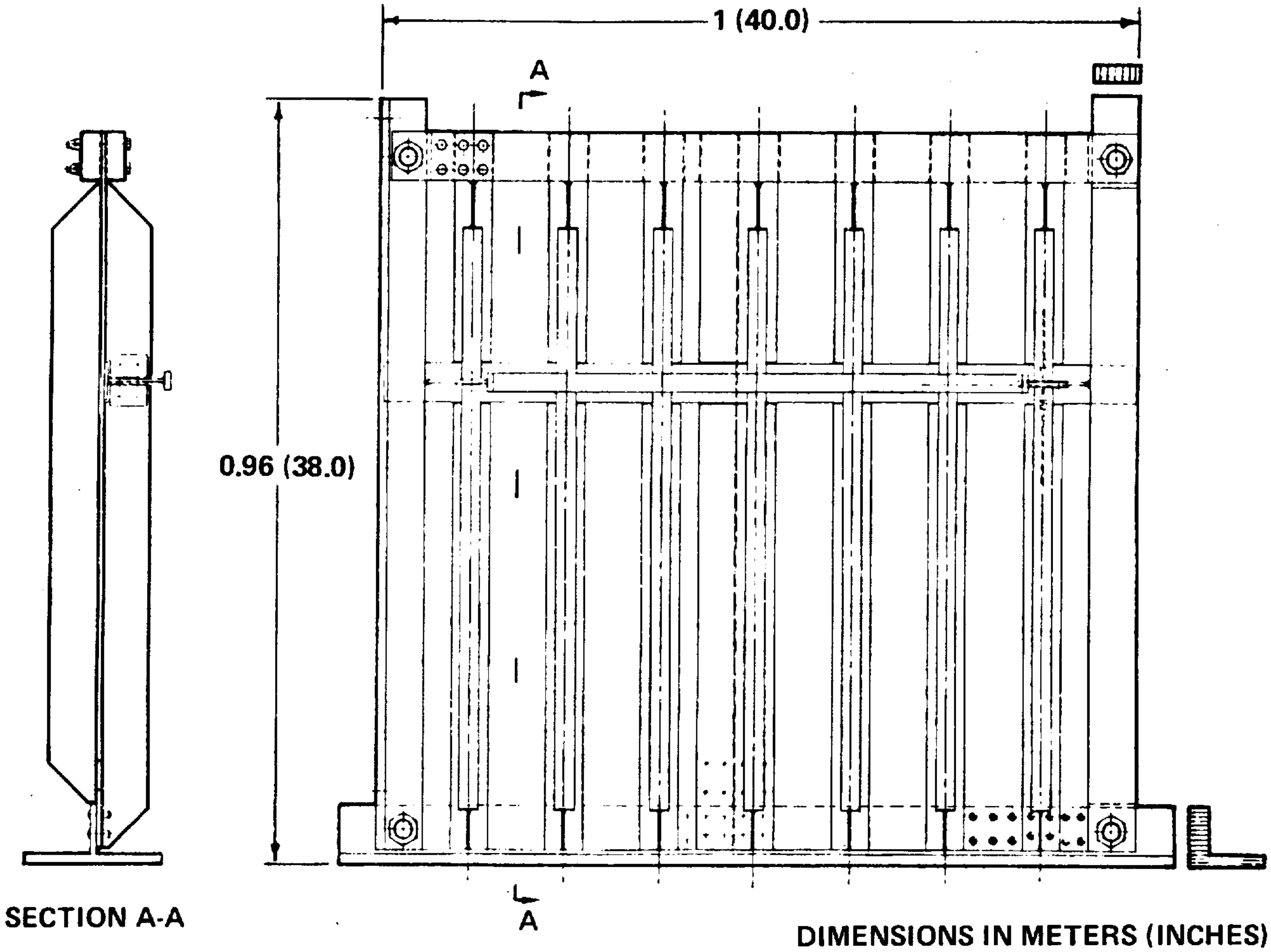


Figure 4-1. Shear Beam Component

wide, 5.8 cm (2.30 in.) wider than the other stiffeners. These wide flanges were used to splice the two panels that constitute the web of the shear beam. The horizontal stiffener is deeper than the vertical stiffeners and was made from 0.25 cm (0.102 in.) and 0.52 cm (0.204 in.) thick unidirectional B/Al.

Sufficient diffusion bonded B/Al sheet material was initially purchased to:

a. Fabricate the 21 vertical stiffeners and the one horizontal stiffener.

b. Develop all of the resistance spot welding and resistance spot joining schedules necessary for attaching the stiffeners to the other details of the shear beam.

c. Fabricate one 48 cm (18 in.) long vertical stiffener and one 48 cm (18 in.) long horizontal stiffener to optimize the brazing parameters prior to making the full-size parts.

d. Provide one flexural fatigue and one tension specimen from each panel for quality control testing.

Approximately 30% of the B/Al purchased to fabricate the I-section stiffeners was damaged by a vendor and had to be replaced. All panels were ultrasonically C-scanned and found to be well consolidated and acceptable. The quality control specimens removed from each panel for flexural fatigue and tension testing resulted in acceptable values (see Section 2).

The ±45° crossply B/Al panels for the bases of the web splice stiffeners were heat treated by solution treating them for 30 minutes at 799K (980F), quenching in cold water, soaking in liquid nitrogen for 5 minutes, and then aging for 8 to 12 hours at 450K (350F).

All material for the I-section stiffeners, the weld schedule development specimens, and the quality control coupons were cut from the diffusion bonded B/Al panels using the diamond disc cutoff saw discussed in Section 3. This is a low cost and precise cutoff method capable of yielding a finished edge so that assembled structures do not require secondary finishing steps.

All stiffeners were fabricated using the Con Braz joining process. A combination heating and tooling module was designed and fabricated for Con Braz joining the I-section stiffeners. The module is stationary and the parts to be joined are hand-fed through the module by the operator, who watches the brazing operation from above. The length of the finished component is limited only by the length of the available material and floor space.

The module uses three 1200-watt T3 quartz radiant heat lamps in three Research Incorporated Model 5305A strip heaters to heat the part to the brazing temperature. These units have a 15.2 cm (6 in.) long polished aluminum reflector that concentrates the radiant heat over a 3.8 cm (1.5 in.) wide by 15.2 cm (6 in.) long target area. The lamp units are water cooled to prevent overheating of the reflector and the lamp ends. Overheating oxidizes the reflector, thus increasing the emissivity of the reflector surface and reducing the efficiency of the heating unit. The quartz lamp end seal temperatures must be maintained below 589K (600F) to ensure a satisfactory lamp life. If the seal temperature exceeds this limit, oxidation of the element at the junction with the quartz envelope is accelerated and the lamp life is considerably reduced.

To try out the module, tooling was initially fabricated to make a 12.7 mm (0.5 in.) thick T-section, since in the original design for the shear beam component, this was to have been the maximum thickness section to be joined. The tooling consisted of two identical stages with springloaded stainless steel rolls that guided the part through the module and maintained an even pressure on the individual part details to ensure intimate contact at the joint area during brazing. Figure 4-2 shows the tooling for one stage of the module and the arrangement of the radiant lamp heating units. To improve efficiency and reduce stray glare from the lamps, polished aluminum reflectors were added between the lamps forming a chamber with open ends. The top was left partly open to allow visual examination of the joint during brazing.

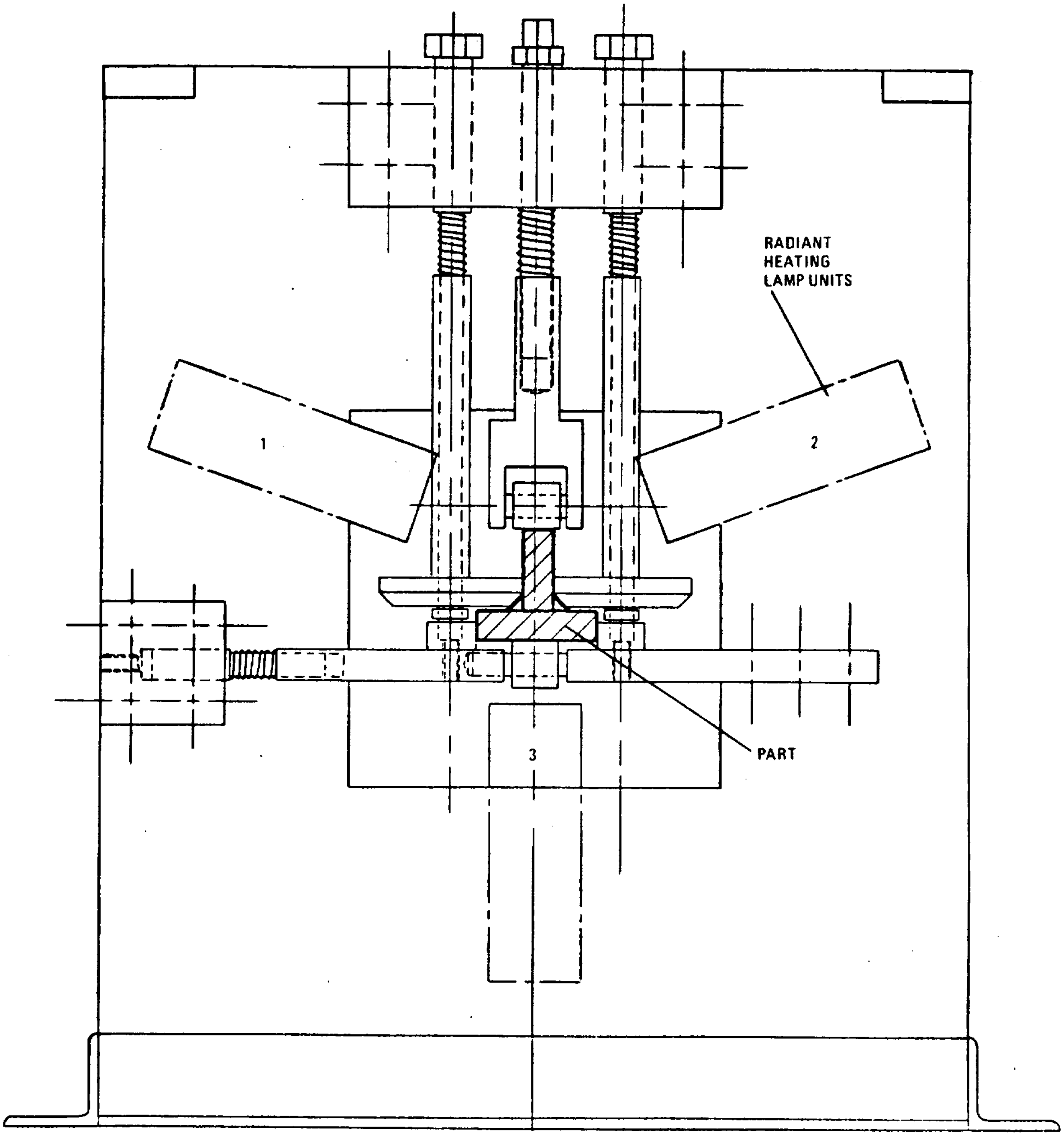
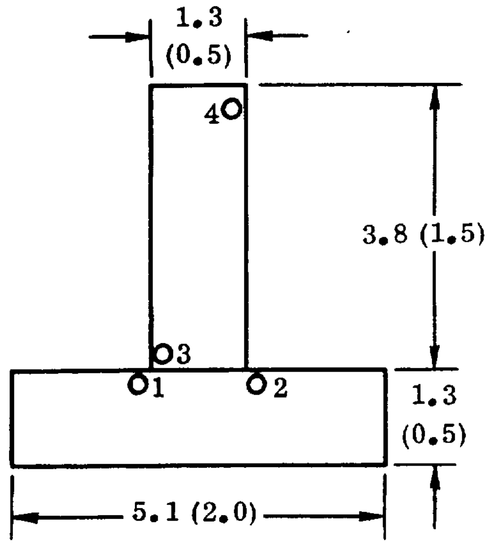


Figure 4-2. Tooling for Con Braz Joining T-Sections

An extractor system was installed over the unit to remove any fumes generated during the brazing operation. This was constructed from clear acrylic sheet to allow unrestricted visibility of the braze joint by the operator. Figure 4-3 shows the Con Braz joining module being used to fabricate an I-section stiffener.

Heating and brazing tests were conducted using 12.7 mm (0.5 in.) thick 6061 aluminum T-sections. Static heating tests were conducted to verify the ability of the strip heaters to bring the part to 700K (800F) which would satisfy the requirement for the braze alloy to be used. Figure 4-4 shows a cross section of the 6061 aluminum T-section used for the static heating and brazing tests and indicates the location of the thermocouples during the static heating studies. Figure 4-5 shows the heating rates obtained using the test section. A 12.7 mm (0.5 in.) thick section can be continuously brazed at a rate of about 7.6 cm/min (3 in/min). Preheating of the part by conduction in a continuous operation would result in a faster brazing rate than the static heating tests indicate. Another mode of operation considered requires reducing the heating intensity so that the part reaches an equilibrium temperature of 700K (800F) after approximately five minutes. This procedure eliminates the risk of overheating the part and permits improved control using an incremental manual feed system.

Figure 4-3. Con Braz Joining of Boron/Aluminum I-Section Stiffener (128749B)



NOTES:

1. O = Thermocouples

2. Dimensions in cm (in.)

Figure 4-4. Cross Section of 6061 Aluminum T and Thermocouple Locations

The maximum heating rate and maximum speed could then be effectively utilized by installing a closed-loop control system. This would consist of a radiation pyrometer sighted on the part with a feedback to a temperature controller that transmits, to the power controller, a signal proportional to the temperature deviation from setpoint. The power controller would then regulate input to a drive motor, which would drive the part through the module at a rate sufficient to maintain the area being brazed at the setpoint temperature.

During initial testing, a 45.7 cm (18 in.) long 12.7 mm (0.5 in.) thick 6061 Al T-section of the same cross section as that shown in Figure 4-4, with preplaced 6061 aluminum fillets and preplaced 0.1 mm (0.005 in.) thick 95% cadmium, 5% silver braze alloy, was Con Braz joined using the module. The large mass of the section was such that the part did not cool adequately when exiting from the module at 7.6 cm/min (3 in/min). This meant the feed rate and lamp intensity had to be reduced to prevent overheating of the section in the heating zone. However, the reduced section of the stiffeners for the shear beam was such that their cooling rate was sufficient to permit use of the maximum heating intensity and feed rate of the module. (Had the cooling rate continued to be a limiting factor, an auxiliary cooling coil could have been added to the exit side of the module.)

Following these development tests it was concluded that the Con Braz module was suitable for fabricating the I-section stiffeners for the shear beam. Optimization of tooling, heating rates, and brazing techniques was accomplished using 45.7 cm (18 in.) long B/Al parts of the same configuration as the stiffeners for the shear beam.

All stiffeners were joined in the Con Braz joining module using Allstate 105, a 95% cadmium 5% silver braze alloy. Details of the joining process are given in process Specification 0-73541 found in the appendix to this volume. To encourage wetting of the B/Al joint surfaces by the braze alloy, the details were electroless nickel plated. This method is part of an established procedure at Convair and is included in the process specification.

The size of the stiffener details exceeded the plating capabilities of existing equipment at Convair. To qualify Pacific Southwest Airmotive (PSA), San Diego, as an outside

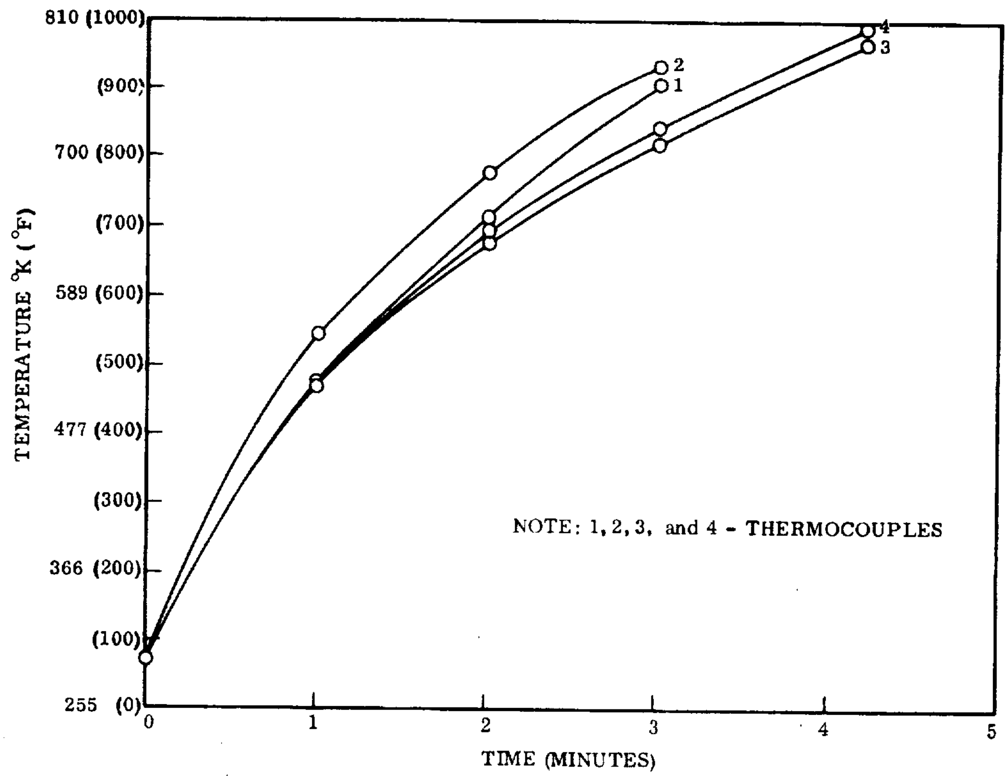


Figure 4-5. Static Heating Rate - 1.3 cm (0.50 Inch) Thick 6061 Aluminum T-Section

vendor for electroless nickel plating, three 1 mm (0.040 in.) thick B/Al lap shear specimens were electroless nickel plated at PSA and then brazed at Convair. Three specimens were also prepared in the same way with 0.005 mm (0.0002 in.) of cadmium plated over the electroless nickel. Since the braze alloy to be used, Allstate No. 105, is 95% cadmium, the cadmium plating was evaluated to determine if it would improve wetability of the surface and encourage better flow of the braze alloy. Two 3.8 mm (0.15 in.) thick by 10 cm (3 in.) long B/Al T-sections were also Con Braz joined using the nickel and nickel/cadmium plating systems. The lap shear tests (Table 4-2) show that the vendor's electroless nickel plating resulted in an average lap shear strength of 88 MN/m^2 (13 ksi) compared to the 81 MN/m^2 (12 ksi) obtained with the Convair electroless nickel system (Section 3). The use of the cadmium overlay produced lap shear strengths of 71 MN/m^2 (10 ksi). Ultrasonic C-scans of the Con Braz joined T-sections indicated that the electroless nickel-plated joint was completely wetted whereas 50% of the cadmium/nickel plated joint was of questionable quality.

The use of cadmium over the nickel offers no improvement in brazing ease or joint strength and could possibly be detrimental. On the basis of these results, the Con Braz joined parts for the stiffeners were electroless nickel plated by the vendor without the cadmium overlay.

Table 4-2. Lap Shear Tests with Electroless Nickel and Electroless Nickel/Cadmium Plating Systems

Test Number	Strength MN/m^2	Strength psi	Failure* Mode
E1 (Nickel only)	78	11,400	1
E2 (Nickel only)	110	15,900	2
E3 (Nickel only)	75	10,860	1&2
Average	88	12,720	
EC1 (Nickel and cadmium)	60	8,690	1
EC2 (Nickel and cadmium)	73	10,700	2
EC3 (Nickel and cadmium)	81	11,700	1
Average	71	10,360	

*1. Interlaminar failure of composite.
2. Adhesive and cohesive failure of braze alloy.

The concept for Con Braz tooling of the I-section stiffeners was essentially the same as that used during the module development phase with the addition of guide rolls to maintain a 90-degree angle between the web and the caps. The sections were joined with the Con Braz heating/tooling module in two passes. The first pass made a T-section and the next pass brazed the second cap on to give an I-section.

Optimization of the operating procedure for the heating/tooling module was achieved by making a 48 cm (18 in.) long vertical I-section stiffener. The two radiant lamp units at the top of the module were directed at the bottom of the web of the part. The radiant lamp under the base of the section was located close to the part to promote maximum heating from the bottom. This method reduced the possibility of melting the joint at the top of the part when the second cap was being joined to the T to make the I-section.

Static heating tests were conducted, using the 48 cm stiffener details, to determine the power input required to produce an equilibrium temperature of 700K (800F), the brazing temperature for Allstate 105, at the joint area. Figure 4-6 shows this optimized heating rate. At this heating intensity, overheating of the part and its subsequent detrimental effects will not occur. With a manually fed mode of operation this rate provides improved control and permits incremental feeding of the part through the unit.

The 48 cm long I-stiffener was made in two passes, as previously discussed. The areas adjacent to the joint were protected by brushing on a thin coat of Nicrobraze

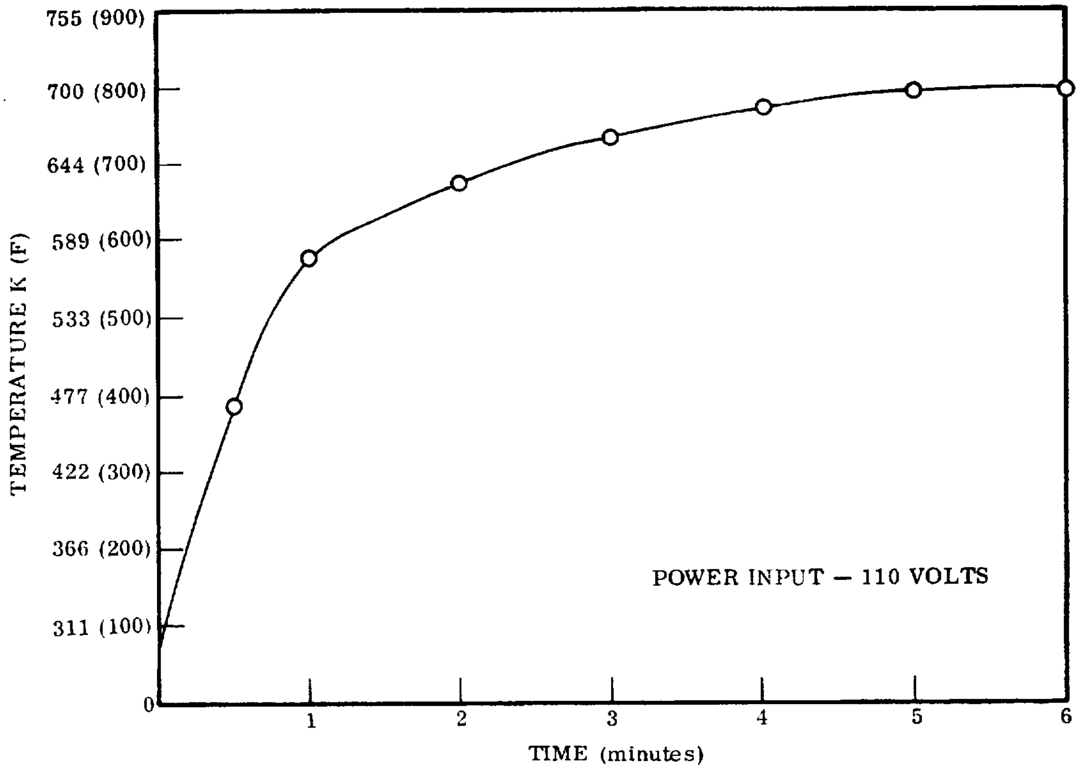


Figure 4-6. Optimized Heating Rate for Con Braz Joining of Vertical Stiffeners

Red, a brazing stopoff agent. The stopoff prevented both staining of the surface by excess flux and excessive wetting of the part by unrestricted flow of the braze alloy. The joint area was prefluxed with Allstate 105 flux followed by preplacement of the Allstate 105 alloy at the joint area. The details were fed through the module and observations made to determine when the braze alloy melted and flowed through the joint. Any inadequately brazed areas were supplemented by hand feeding a prefluxed braze rod into the required area. The part was fed through the module at a speed consistent with producing a good joint of uniform quality. Ultrasonic C-scan inspection of both joint surfaces indicated excellent joints.

Prior to Con Braz joining, all B/Al I-section details were machined at Convair and then electroless nickel plated by PSA. This type of work had been subcontracted to PSA on many previous occasions with excellent results. Due to processing difficulties at PSA, approximately 30% of the I-section details had to be scrapped and replacement material purchase. The aluminum surface of the composite had been excessively etched and exposed boron was evident over a large percentage of the plated surfaces of these details. This resulted in brazing difficulties and an unacceptable reduction in the joint strength because the adhesion strength of the nickel plating to the boron was poor.

Replacement material was purchased, machined to size, and electroless nickel plated by PSA with Convair engineering personnel in attendance during all processing stages to ensure that satisfactory parts were produced. Boron/aluminum quality control specimens for lap shear tests were processed along with the details and then brazed and tested to determine the quality of the plating and the joints (see Table 4-3).

Table 4-3. Lap Shear Test Results

Specimen No.	Shear Strength	
	MN/m^2	(ksi)
QC 1	97	14.1
QC 2	85	12.3
QC 3	78	11.3
Average	87	12.6

The average value of 87 MN/m^2 (12.6 ksi) is typical of joint strengths previously obtained.

Con Braz joining with the heating/tooling module allowed close temperature control at the joint area. With other brazing techniques this control is difficult when thin gage material is being brazed. The equilibrium temperature control system for the Con Braz joining module allows the joint area of the part to be held at the brazing temperature for an indefinite period of time without any risk of overheating. This promotes a good flow of the braze alloy and allows careful examination of the joint during brazing.

The horizontal stiffener and the splice stiffener caps were torch brazed using an oxygen-gas torch since the small length of joint involved could not justify modifying the Con Braz module to physically accommodate the increased dimensions of these details.

The fixtures used to hold the B/Al details in the correct position during torch brazing are shown in Figure 4-7. Torch brazing was considerably slower than brazing with the Con Braz joining module because assembling and aligning the part details had to be accomplished manually before brazing, whereas the spring loaded rolls of the Con Braz joining module align the details automatically. With torch brazing, heating was effected over a much smaller area and controlling the joint temperature was more difficult, requiring considerably more skill and care by the operator than necessary when using the Con Braz joining module. Also, brazing was interrupted for fixture relocation (to provide access to all areas of the joint).

All 21 vertical stiffeners and the horizontal stiffener were successfully joined. This involved in excess of 24.5m (80 ft) of Con Braz joining with 1.5m (5 ft) being rejected due to inferior nickel plating. No failures of the radiant quartz lamps in the heating units occurred. When using the equilibrium temperature control system and feeding the part manually through the Con Braz joining module, the brazing speed was approximately 3.8 to 5 cm (1.5 to 2 in.) per minute. Modification of the module to include automatic control and permit full use of the maximum heating capability can increase the feed rate to about two to three feet per minute.

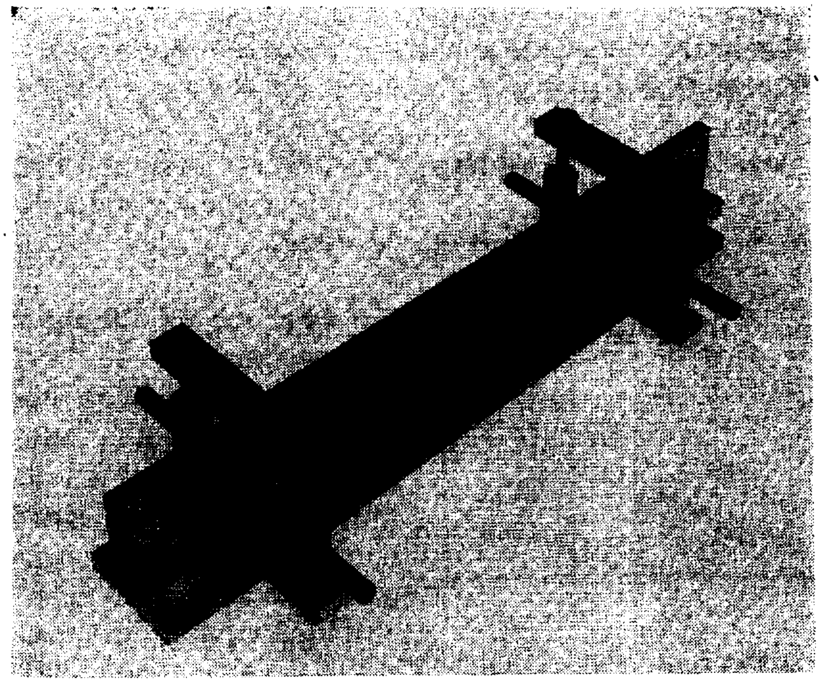


Figure 4-7. Fixture for Con Braz Joining I-Sections Using a Torch (119422B)

The vertical I-section stiffeners were Con Braz joined with ends perpendicular to the base to simplify the tooling and joining operations. The stiffeners subsequently required cutting to a 45-degree angle on the ends adjacent to the test fixture and undercutting the base of the vertical stiffeners at the ends that intersect with the horizontal stiffener. The latter operation was necessary to prevent interference of the vertical stiffener with the base of the horizontal stiffener. The 45-degree angle was machined by rough cutting the excess material from the parts using a standard silicon-carbide cutting wheel. The surfaces were then face milled with a 10.1 cm (4 in.) diameter diamond plated planer mill using sulfo-chlorinated oil as a cutting fluid. The undercut areas of the vertical stiffeners were milled using the same cutter and machining conditions.

4.1.2.2 Web Fabrication. Fabrication of the shear beam web consisted of material procurement and qualification testing, heat treatment, and machining.

Two diffusion-bonded crossply B/Al panels, one 48 × 113 × 0.551 cm (19 × 44.5 × 0.217 in.) and one 55 × 113 × 0.551 cm (21.5 × 44.5 × 0.217 in.) were purchased for the web of the shear beam. The panel sizes included sufficient material to develop all of the resistance spot welding and resistance spot joining schedules necessary for attachment of shear beam details to the web. Material was also available for tensile and flexural fatigue specimens from each panel for quality control testing. Both panels were distorted when received. The distortion was attributed to the step processing techniques used by the supplier. The distortions were distinct bends that ran across the total width of the panels in two locations (i.e., at the location of the "steps" during primary processing).

The panels were solution treated, cryogenically soaked, and then aged. The solution treatment consisted of 30 minutes at 799K (980F) followed by a water quench. The cryogenic soak consisted of five minutes in liquid nitrogen, i.e., 77K (-320F). The panels were aged at 450K (350F) for 9 to 12 hours in an aluminum fixture. The aging fixture was designed to bend the panel flat by creep forming during the aging cycle. The amount of deflection imposed upon the panel allowed for springback upon removing the panel from the aging fixture. The panels were aged in three-hour increments, removed from the fixture and examined, and reassembled in the fixture for further adjustments to obtain a flat panel. Two or three adjustments were necessary before the panels were flat enough to ensure proper fit with the I-section stiffeners during resistance spot welding.

The two B/Al panels were cut to their final sizes of 0.563 × 48.00 × 95.58 cm (0.217 × 18.9 × 37.63 in.) and 0.563 × 53.59 × 95.58 cm (0.217 × 21.10 × 37.63 in.) using the diamond disc cutoff saw. Weld schedule development specimens and quality control coupons were cut from the B/Al panels.

4.1.2.3 Compression Cap. The compression cap assembly for the shear beam consisted of a titanium T-section with its base attached to a thick B/Al beam member. One end of the beam was designed for a horizontal compression load of 889.6 kN (200,000 lb) and the other end for a reaction load of 1356.6 kN (300,000 lb). The leg of the titanium T was resistance spot joined to the crossply B/Al web during final assembly.

The 0.3 cm (0.125 in.) thick 6Al-4V-titanium T-section detail of the compression cap was machined and heat treated by a vendor. A 6.4 × 8.9 cm (2.5 × 3.5 in.) hot-rolled and annealed 6Al-4V titanium bar was purchased to make the T. A laboratory report from the supplier indicated that heat treatment per AMS 4967 would result in a tensile strength of 1020 MN/m^2 (148 ksi), which adequately satisfied the design requirements.

To ensure good fit between the base of the T-section and the B/Al cap and between the leg of the T-section and the B/Al web, the TIR over any 46 cm (18 in.) length of the T-section was held to a maximum of 0.13 mm (0.005 in.) and to a maximum of 0.25 mm (0.010 in.) over the full 1m (40 in.) length of the part. This requirement applied to all surfaces of the titanium T-section and was achieved by rough machining the as-received 6Al-4V-titanium bar to the T shape with approximately 0.3 cm (0.125 in.) excess material on all surfaces. The part was then heat treated before final machining.

The diffusion-bonded B/Al beam for the compression cap assembly is 125 cm (50 in.) long, 13.3 cm (5.25 in.) wide and tapers in thickness from 1.7 cm (0.64 in.) at one end down to 1.2 cm (0.44 in.) at the other end. The beam is unidirectional with the boron filaments running in the 125 cm (50 in.) direction. The beam was purchased in the tapered configuration from Amercom Inc., the B/Al supplier, and only required cutting to the proper length and width before assembly. The beam was fabricated so that the surface to be attached to the titanium T was flat. The beam was ultrasonically inspected upon receipt and found to be of uniform and well bonded quality.

The titanium T-section was attached to the B/Al beam using sixty 0.64 cm (0.25 in.) diameter titanium hi-shear pins. The holes were drilled first in the titanium T-section using high-speed steel drills and conventional machining techniques. The T-section was then used as a drill template for drilling the 0.64-cm (0.25 in.) diameter holes in the B/Al beam. These holes were drilled using diamond core drills and the Branson UMT-3 Rotary Ultrasonic Machine (RUSM) discussed in Section 3. Details of the drilling process are given in process Specification 0-73540 Drilling, Boron/ Aluminum Composite, Specification for found in Appendix A.

Four type 4340 steel loading pads were attached to both surfaces of the B/Al cap at each end. Then each of the two load bearing surfaces were machined flat and parallel using a 28 cm (11 in.) diameter diamond plated face mill with 20/40 diamond grit size.

4.1.2.4 Shear Beam Weld Assembly. The overall assembly sequence for the shear beam, with weld schedules indicated in parentheses, is listed below:

a. Join the unidirectional B/Al cap to the 6Al-4V-titanium T-section with mechanical fasteners.

b. Attach tension cap test fixture details to the two B/Al web panels with mechanical fasteners.

c. Resistance spot join the 0.33 cm (0.125 in.) thick leg of the 6Al-4V titanium T-section to the 0.55 cm (0.217 in.) thick crossply B/Al web panels (SB-I).

d. Resistance spot weld the 0.26 cm (0.102 in.) thick unidirectional B/Al cap of the horizontal stiffener to the 0.55 cm (0.217 in.) thick crossply B/Al web panels (SB-II).

e. Attach all of the vertical stiffeners to the test fixture details and to the B/Al web panels (at the test fixture area only) using mechanical fasteners.

f. Resistance spot weld the two 0.28 cm (0.109 in.) thick crossply B/Al caps of the web splice stiffeners to the 0.55 cm (0.217 in.) thick crossply B/Al web panels (SB-III).

g. Resistance spot weld the 0.17 cm (0.068 in.) thick unidirectional B/Al cap of the remaining 18 vertical stiffeners to the 0.55 cm (0.217 in.) thick crossply B/Al web panels (SB-IV).

h. Resistance spot weld the 0.28 cm (0.109 in.) thick crossply B/Al caps of the two web splice vertical stiffeners to the B/Al side of the previously resistance spot joined 0.33 cm (0.125 in.) thick 6Al-4V titanium T and 0.55 cm (0.217 in.) thick crossply B/Al (SB-VII).

i. Resistance spot weld the 0.17 cm (0.068 in.) thick unidirectional B/Al caps of the remaining 18 vertical stiffeners to the B/Al side of the titanium-B/Al resistance spot joint (SB-VIII).

j. Resistance spot weld the caps of the horizontal stiffener and the web splice stiffener to the web at their intersections (SB-V).

k. Resistance spot weld the caps of the vertical stiffeners and the web splice stiffener to the web at their intersections (SB-VI).

l. Attach the aluminum shear clips to the vertical and horizontal stiffeners, at their intersections, with mechanical fasteners.

m. Assemble the remaining details of the test fixture around the shear beam and drill and fasten as required.

The resistance spot joining of 0.55 cm (0.217 in.) thick crossply B/Al to 0.318 cm (0.125 in.) thick 6Al-4V titanium and then joining 0.173 cm (0.068 in.) thick unidirectional B/Al to this assembly (SB-VIII) represented a considerable advance in the joining technology for B/Al. The titanium was spot joined to the thick B/Al (Figure 4-8), and then a high heat impulse sent through the B/Al to B/Al joint to form the second joint without degrading the first joint. Following the resistance spot joining of the B/Al to the titanium, it was necessary to sand the titanium surface to remove uneveness resulting from electrode indentation before making the second resistance spot joint.

Table 4-4 gives the details of all of the weld schedules used to weld the shear beam. To obtain access to the weld locations, it was necessary to fabricate special electrode holders. The holders were fabricated with cut-outs (Figure 4-9 left) for access around the stiffener caps. To produce the intersection welds (SB-V and SB-VI), one holder was further modified (Figure 4-9 right). A large steel pipe support was added to stiffen the modified electrode. Because of the weight of the shear beam, a set of jack-type leveling supports was built, and a crane was used to position the beam. The weld setup is shown in figure 4-10. Weld electrode positioning during welding is illustrated in Figure 4-11. The results of the shear beam weld schedule test samples are listed in Table 4-5. Joint efficiencies were 70% or greater in the spot welds and 60% or greater in the spot diffusion joints.

During examination of the shear beam after welding, it was observed that the compression cap assembly was five degrees off the vertical plane. This was caused by excessive heating of the titanium T-section during welding. The subassembly was straightened to within one degree by shot peening the inside radius of the titanium T-section.

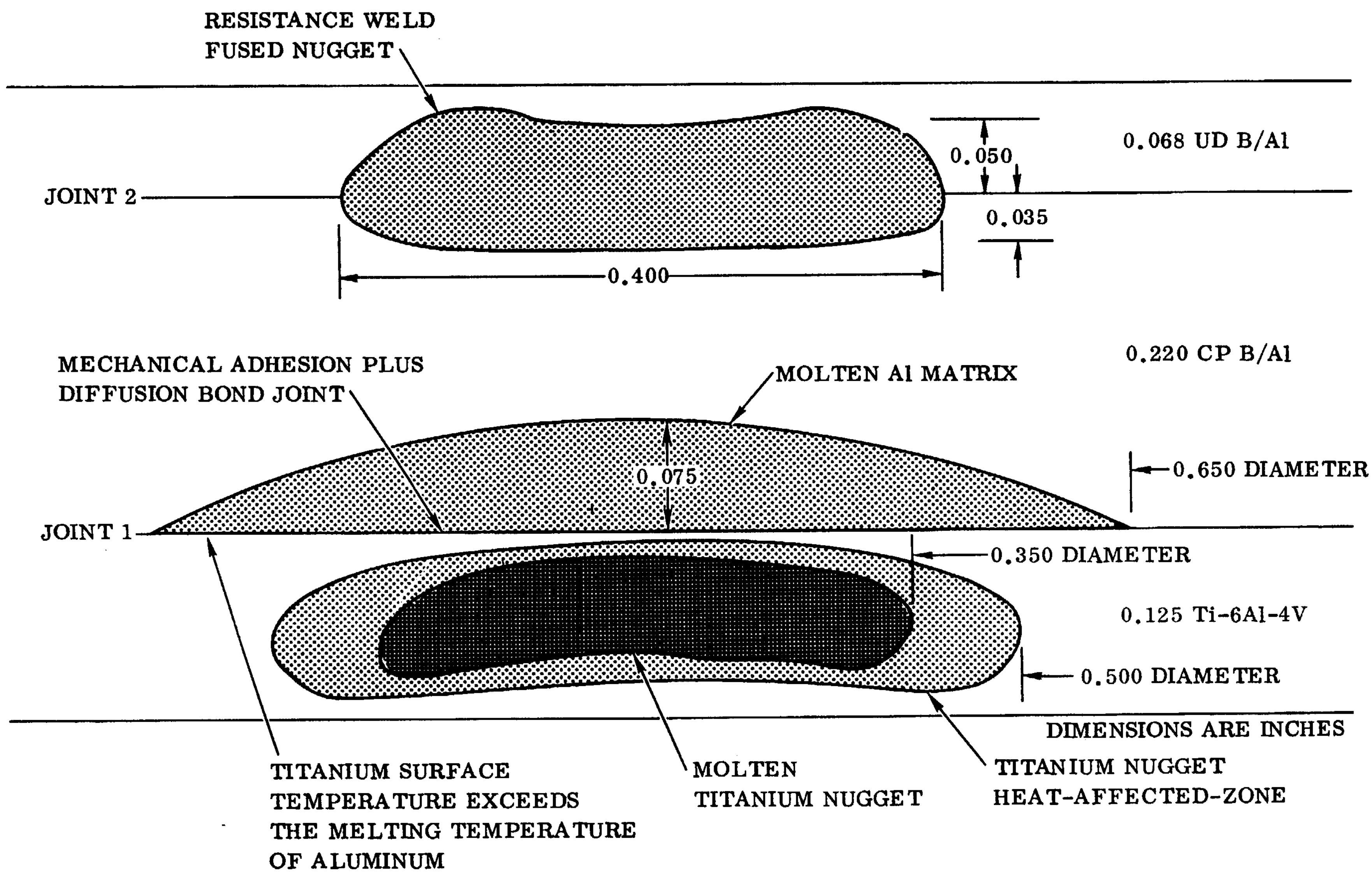


Figure 4-8. Resistance Spot Joint Test Configuration

Table 4-4. Weld Schedules Used for the Shear Beam Joints

Weld Schedule	SB-I	SB-II	SB-III	SB-IV	SB-V	SB-VI	SB-VII	SB-VIII
Weld Joint Description	Web to Ti Tee	Web to Frame (Horizontal Stiffener)	Splice to Web to Splice	Stiffener to Web to Stiffener	Frame to Web to Splice	Frame to Web to Stiffener	Splice to Web to Ti Tee	Stiffener to Web to Ti Tee
Top Sheet: Material and Thickness, cm (in.)	CP B/Al 0.550 (0.217)	6061 Al* 0.318 (0.125)	CP B/Al 0.277 (0.109)	UD B/Al 0.173 (0.068)	UD B/Al 0.256 (0.102)	UD B/Al 0.256 (0.102)	6061 Al* 0.229 (0.090)	6061 Al* 0.229 (0.090)
Second Sheet: Material and Thickness, cm (in.)	Ti-6Al-4V 0.318 (0.125)	UD B/Al 0.256 (0.102)	CP B/Al 0.550 (0.217)	CP B/Al 0.550 (0.217)	CP B/Al 0.550 (0.217)	CP B/Al 0.550 (0.217)	CP B/Al 0.277 (0.109)	UD B/Al 0.173 (0.068)
Third Sheet: Material and Thickness, cm (in.)	—	CP B/Al 0.550 (0.217)	CP B/Al 0.277 (0.109)	UD B/Al 0.173 (0.068)	CP B/Al 0.277 (0.109)	UD B/Al 0.173 (0.068)	CP B/Al 0.550 (0.217)	CP B/Al 0.550 (0.217)
Fourth Sheet: Material and Thickness, cm (in.)	—	—	—	—	—	—	Ti-6Al-4V 0.318 (0.125)	Ti-6Al-4V 0.318 (0.125)
Preheat Weld Heat, Impulses	2-20	2-12	2-4	2-4	2-4	2-4	2-2	2-2
Weld Cool Time (cycles)	6-4.5	8-4.5	9-5.5	9-5.5	9-5.5	9-5.5	8-4.5	7-4.5
Weld Heat (% Phase Shift)	23-36	45-59	37-58	37-55	37-58	37-56	45-75	45-72
Forge Delay Initiation and Time (cycles)	Weld Start 8.5	Weld End 1.2	Weld Start 19.6	Weld Start 19.6	Weld Start 19.6	Weld Start 19.6	Weld End 1.2	Weld End 1.2
Weld Pressure kN (lb) Forge Pressure kN (lb)	8.9 (2000) 13.4 (3000)	6.7 (1500) 11.1 (2500)	6.7 (1500) 11.1 (2500)	6.7 (1500) 11.1 (2500)	6.7 (1500) 11.1 (2500)	6.7 (1500) 11.1 (2500)	4.9 (1100) 9.4 (2100)	4.9 (1100) 9.4 (2100)

* Peel Strip

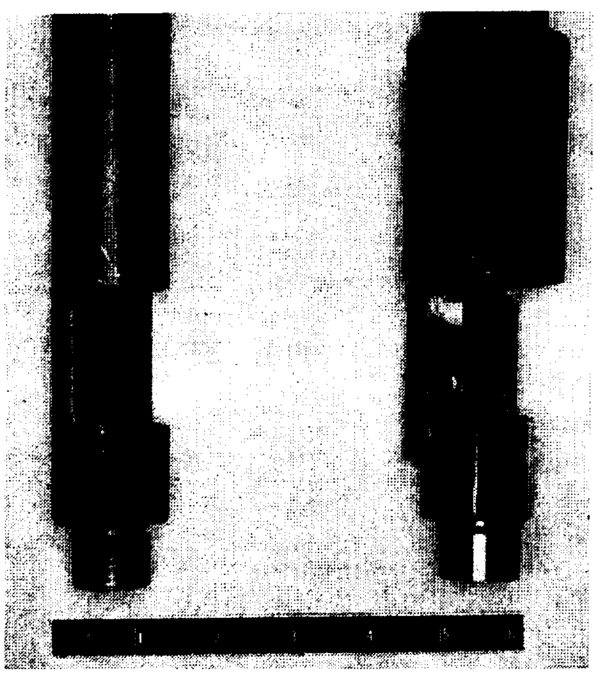


Figure 4-9. Electrode Holders Used to Fabricate the Shear Beam (128960B)

Figure 4-10. Shear Beam Welding Setup (127478B)

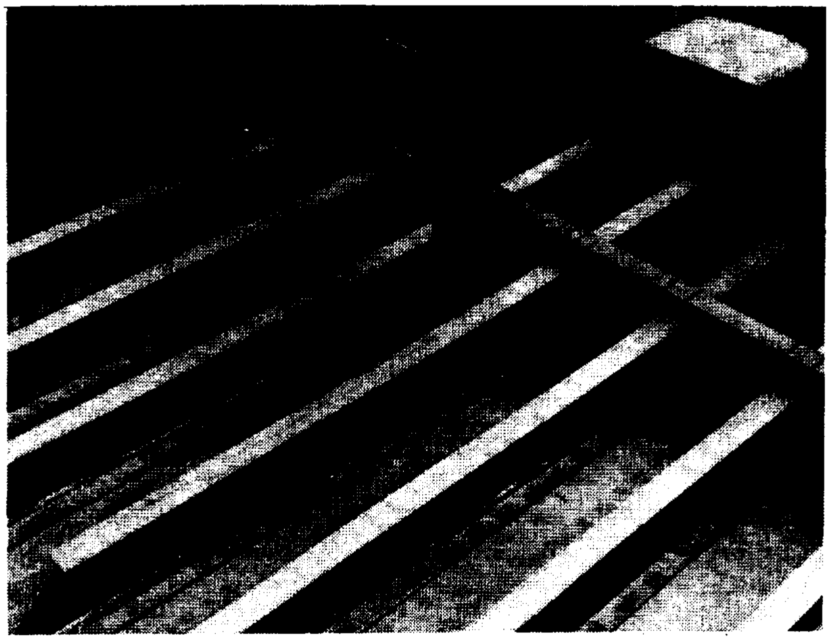


Figure 4-11. Resistance Spot Welding of Shear Beam (127479B)

Table 4-5. Weld Schedule Test Results for Shear Beam Joints

Weld Schedule	SB-I	SB-II	SB-III	SB-IV	SB-V	SB-VI	SB-VII	SB-VIII
Weld Joint Description	Web to Ti Tee	Web to Frame (Horizontal Stiffener)	Splice to Web to Splice	Stiffener to Web to Stiffener	Frame to Web to Splice	Frame to Web to Stiffener	Splice to Web to Ti Tee	Stiffener to Web to Ti Tee
Average Weld Diameter cm (in.)	1.65 (0.65)	1.27 (0.50)	1.52 (0.60)	1.27 (0.50)	1.27 (0.50)	1.42 (0.56)	1.14 (0.45)	1.14 (0.45)
Average Failure Load Per Spot, kN (lb)	20 (4500)	24.5 (5500)	37.5 (8400)	33.8 (7600)	20.5 (4600)	22.2 (5000)	13.4 (3000)	12.4 (2800)
Average Stress in Failed Member, MN/m^2 (ksi)	91 (13.6)	940 (131)	267 (38.7)	134 (19.4)	162 (23.4)	140 (20.3)	132 (19.0)	123 (17.8)
Failure Mode	Shear	Net Tension	Net Tension	Shear	Shear	Shear	Shear	Shear
Failure Location	Interface	Frame	Web	Interface	Frame to Web Interface	Frame to Web Interface	Splice to Web Interface	Stiffener to Web Interface
Joint Efficiency (%)*	60	70	95	86	100	90	84	79

*Based on 155 MN/m^2 (22.6 ksi) shear strength, 281 MN/m^2 (40.7 ksi) tensile strength in heat-treated cross-ply B/Al, and 1488 MN/m^2 (216 ksi) tensile strength in UD B/Al.

4.1.2.5 Shear Beam Final Assembly. Following assembly of the stiffeners, the web, and the compression cap subassembly, the shear clips (that tie the vertical and horizontal stiffeners together) were installed and the shear beam was drilled and assembled in the steel test fixture.

The 2024-T4 aluminum shear clips that tie the 0.17 cm (0.068 in.) thick vertical B/Al stiffeners to the 0.28 cm (0.109 in.) thick web of the horizontal stiffener were attached by titanium hi-shear mechanical fasteners. The holes for the fastener were punched in the stiffeners. The punching process has proven to be a realistic and economical approach to producing holes in B/Al material up to 0.28 cm (0.110 in.) thick. Strength and fatigue life of composites having punched holes are comparable to composites having diamond-drilled holes (Reference 7). The male and female dies are inexpensive ($1.50 per die set) and are capable of producing several hundred holes.

To facilitate assembly, a hole punching tool, shown on the left in Figure 4-12, was built. This tool was used to punch holes in the B/Al stiffeners. The punch was designed to use a helical screw rather than a simple lever to apply the necessary punching force because of the greater reliability and control over pressure application that is associated with the helical screw concept. A coupling device allows the horizontal force component from the screw to be transformed into the vertical force component of the punch. The design also provides unhindered access to the hole locations, which would normally be inaccessible with commercially available hole punching tools. The punch holder was fabricated from meehanite and was covered with tape to minimize the risk of damage to the shear beam from metal to metal contact during use.

Figure 4-13 shows the hole punching tool being used on a stiffener. An extension wrench was used to turn the screw to allow a constant application of pressure. This improves process reliability and simplifies the hole-punching procedure.

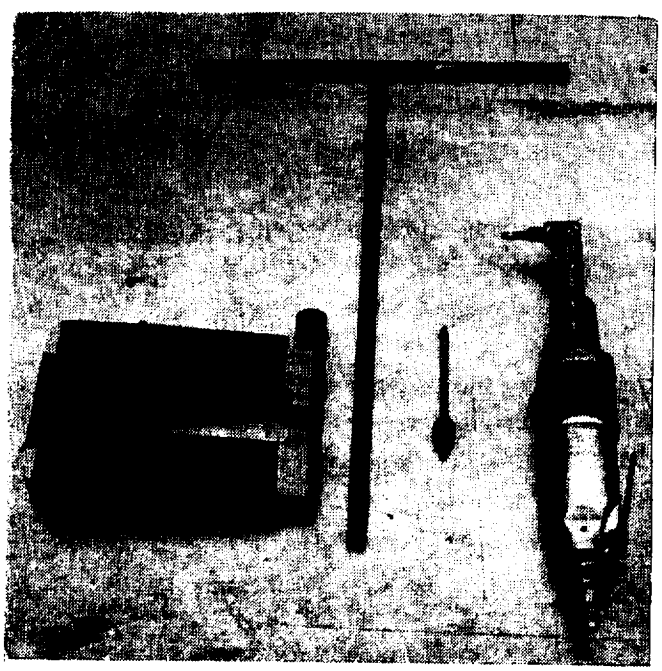


Figure 4-12. Hole Punch and Reaming Tool Used for B/Al Shear Beam (129431B)

To maintain a hole tolerance of +0.05 mm, -0.00 mm (+0.002 in., -0.000 in.), an additional reaming operation was performed. The 90-degree drill and diamond plated bit are shown on the right of Figure 4-12. All punched holes were brought to size using this method. No apparent sign of drill wear was observed.

The holes in the 2024-T4 aluminum clips were drilled with conventional high-speed steel drills. The holes in the first clips were used as a template for the hole-punch operation; then the holes in the B/Al stiffener were used as a template for drilling the holes in the aluminum clip attached to the opposite side of the stiffener web. Drilling, punching, and assembly progressed using this procedure until all four clips at each intersection were installed.

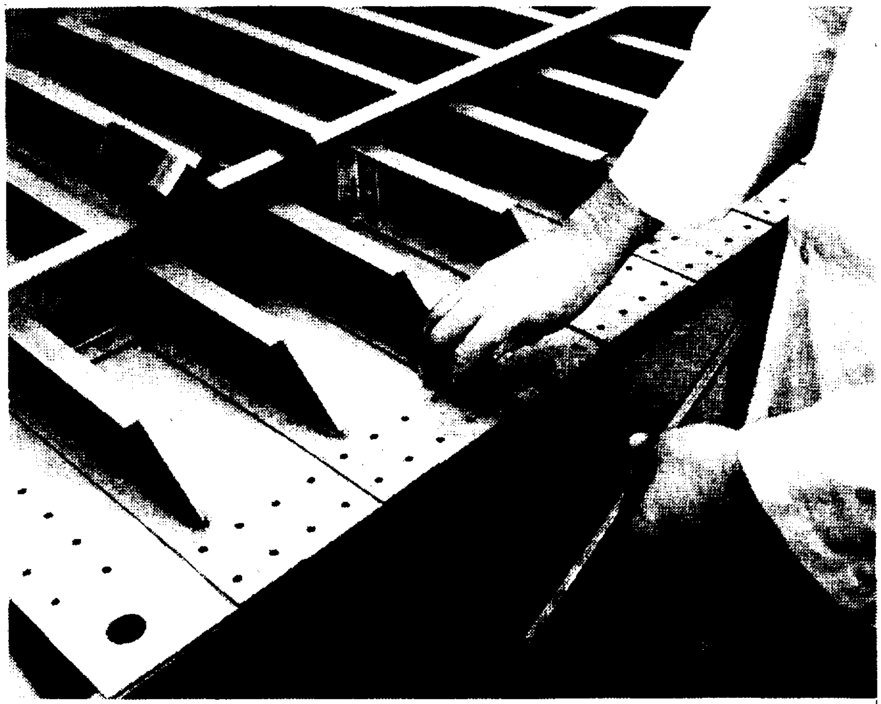


Figure 4-13. Punching Hole in B/Al Stiffeners During Assembly of Shear Clips (129427B)

Attachment of the 4340 steel test fixture to the B/Al shear beam required drilling 142 holes around the periphery of the beam and 24 holes in the ends of the compression cap. All holes were drilled using the rotary ultrasonic (RUSM) drilling machine with diamond impregnated core drills. The 4340 steel test fixture details were used as drill templates to ensure correct location of the holes and alignment with the fixture upon final assembly. The rotary ultrasonic machine was mounted on the swing arm of an Induma mill. The increased throat capabity and larger indexing table allowed better maneuverability of the part and provided more stability during drilling.

Figure 4-14 shows the ultrasonic machine mounted on the Induma mill during drilling of the shear beam. The quantity and size of the holes drilled, drill speed, diamond grit size, and material thickness are listed in Table 4-6. Following drilling the shear beam and test fixture were disassembled, cleaned, and then reassembled for shipment to the Marshall Space Flight Center. Figures 4-15 and 4-16 show the two sides of the completed shear beam.

4.1.2.6 Cost Analysis. No extensive cost analysis was conducted during the program, but the overall cost of fabricating the shear beam was determined. The values reported do not include development costs and the cost of the steel test fixture or titanium T-section. The final cost for the shear beam (including nonrecurring costs such as

Figure 4-14. Final Drilling of the Shear Beam (128748B)

Table 4-6. Parameters for Final Drilling of B/Al Shear Beam

Hole Diameter cm (in.)	Material	No. of Holes Drilled	Drill Speed (rpm)	Diamond Grit Size
2.9 (1.250)	B/Al Web and Ti Tee	1	3000	80
2.5 (1.000)	B/Al Web and Ti Tee	1	3000	80
2.5 (1.000)	B/Al Web	2	3000	80
0.6 (0.250)	B/Al Web & Splice Plates	96	3500	180
1.0 (0.375)	B/Al Web	44	3000	120
1.1 (0.437)	B/Al Cap	12	3000	120
1.1 (0.437)	B/Al Cap	12	3000	120

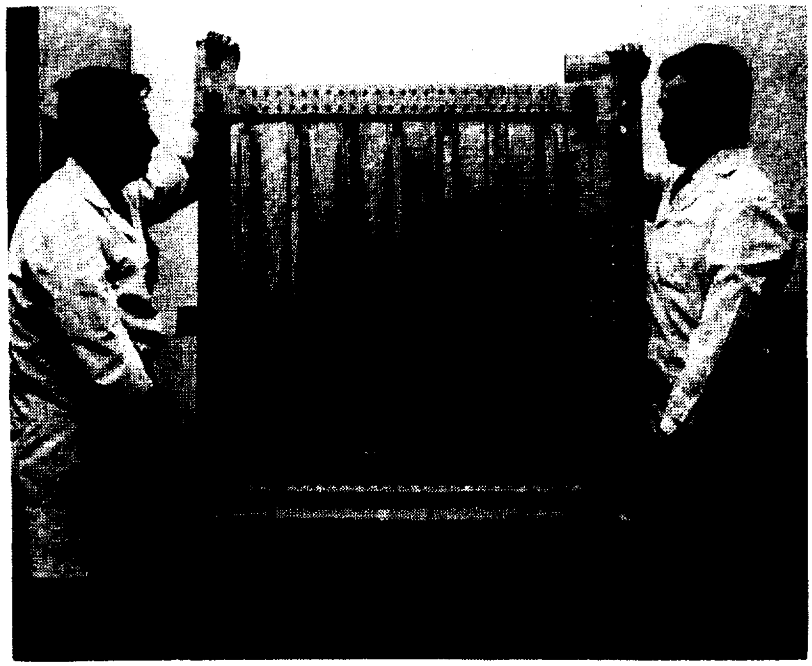


Figure 4-15. Completed Shear Beam and Test Fixture Assembly (129953B)

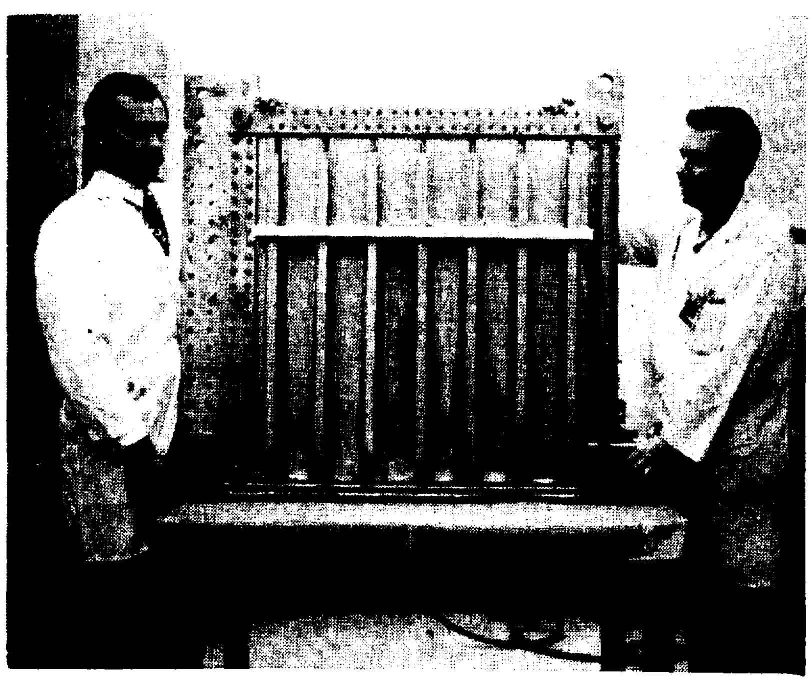


Figure 4-16. Frame Side of Completed Shear Beam and Test Fixture Assembly (129951B)

tooling) was \$73,000. Material costs were \$35,000, and the final panel weight (composite only) was 35.5 kg (78 lb). Therefore, material and fabrication cost for the shear beam was \$2060/kg (\$940/lb) including nonrecurring costs. Tooling costs amounted to \$11,000; consequently, the cost of the shear beam excluding nonrecurring items was \$1880/kg (\$855/lb).

4.2 COMPRESSION PANEL COMPONENT

The 2.03 × 0.74m (80 × 29 in.) uniformly loaded compression panel test component was fabricated by room temperature forming B/Al stringers and resistance welding them to a B/Al skin. Three subcomponent test specimens were prepared in addition to the full size compression panel. Detailed design and analysis of these structures is contained in Volume I.

4.2.1 <u>SUBCOMPONENT DEVELOPMENT AND FABRICATION</u>. The concept of Con Clad forming B/Al panels was developed as a proprietary process by Convair Aerospace, and is discussed in Reference 24. The process entails the use of steel sheet diffusion bonded to the external surfaces of the composite. This steel both aids in increasing the transverse strength of the composite during forming, and, in instances where selective etching is used, shifts the neutral axis in the composite so that most of the composite material is in compression during forming.

Initial development work with Con Clad material was performed using material manufactured in Convair's laboratory; however, facilities in the laboratory were insufficient to produce the 2m (80 in.) long hat section stringers required for the uniformly loaded compression panel. Therefore, work was performed with a vendor (Amercom, Inc.) to develop the necessary bonding parameters for the full-scale Con Clad composite stringers. Two panels, each 15 × 8 × 0.24 cm (6×3×0.1 in.) were made at Amercom. Angle sections having 0.95 cm (0.375 in.) radii were brake-formed from these panels. Sections were made successfully with no indications of cracking. After this was accomplished, a Con Clad panel was purchased to make a 20.3 cm (18 in.) long crippling specimen. The same processing parameters were used for this 64 × 18 × 0.24 cm (25 × 7 × 0.1 in.) panel that were used for the previous panels. The panel was successfully formed to the same cross section as that required for the full-scale stringers (Figure 4-17). The forming was accomplished in the production shop using production personnel and equipment. The rate of forming was similar to that for forming aluminum of the same thickness. The specimen was trimmed to a width of 9.6 cm (3.8 in.) and length of 48 cm (18 in.) using the diamond-plated cutoff saw. Steel end blocks were fabricated and bonded to the ends of the hat section using Hexcel 901 foam, an adhesive used for 589K (600F) applications. The specimen was tested at 589K (600F). A post test evaluation disclosed that the testing arrangement did not provide the desired end fixity. Instead, the specimen acted as the center of a 2m (78 in.) column of undetermined fixity. For this reason, a second crippling test was run.

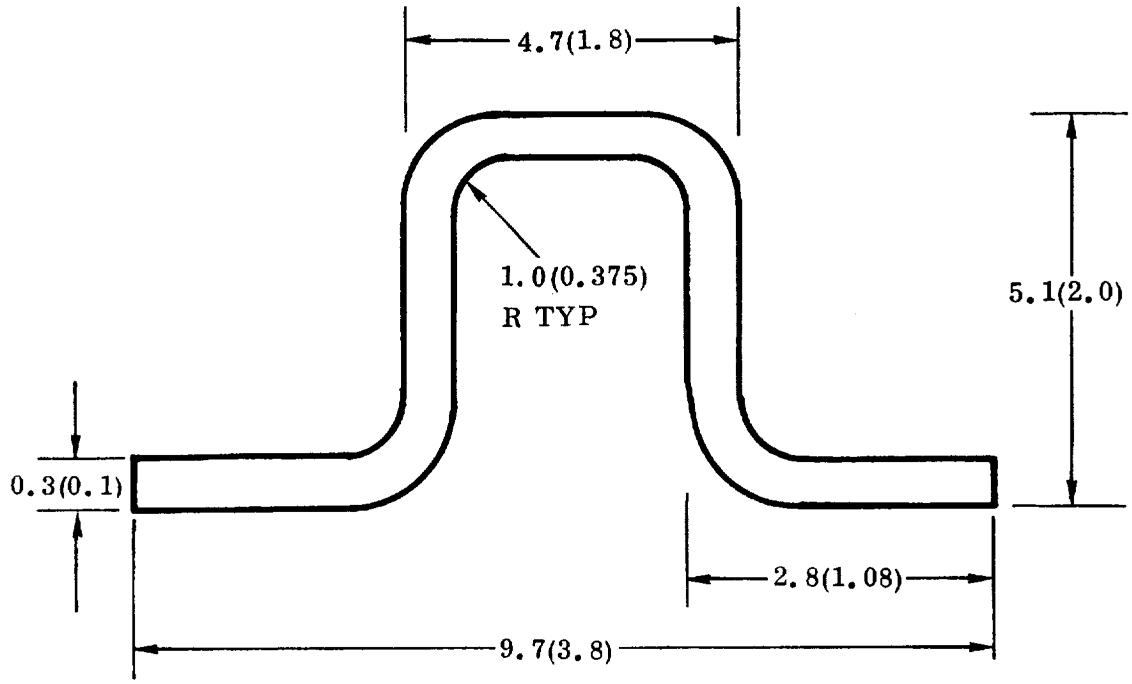


Figure 4-17. Cross Section of Con Clad Hat Stringer

The 46 cm (18 in.) long Con Clad stringer from the first crippling test was disassembled and cut to approximately 30.3 cm (12 in.) for retesting. The crippled section was reformed into the desired configuration by forming at 755K (900F) using wooden tools and graphite lubricant. The hat was resistance welded to a 10-ply 0±45° skin and retested at 589K (600F). The specimen failed at a load of 445 kN (100,000 lb) after sustaining this load for several minutes (during which time the operator was preparing to switch the test machine to a higher load range). (Test details are included in Volume I.) The test substantiated the basic stringer section design and the method of skin-to-stringer attachment and indicated that local crippling would not be a probable failure mode for the panel.

A third subcomponent test was performed on a 36 cm (14 in.) long hat section cut from the spare 2m (80 in.) long hat section. (Six hats, instead of the five required for the panel, were actually formed. The sixth stringer was to serve as a backup.) The forming of this section is described in Section 4.2.2. The hat was cut to length on the diamond disc cutoff saw and assembled in the steel end fitting in the same manner as the previous two subcomponent specimens. The hat exceeded the predicted buckling stress prior to failure.

4.2.2 COMPRESSION PANEL FABRICATION. With the successful completion of the first two subcomponent tests, permission was given to the vendor to prepare the Con Clad panels to be used in the full-scale test specimen. While the B/Al Con Clad panels and crossplied skins were being manufactured, the necessary tooling, steel end caps, etching tanks, and a titanium frame were fabricated. The general configuration of the compression panel is shown in Figure 4-18; detailed design and analysis are given in Volume I.

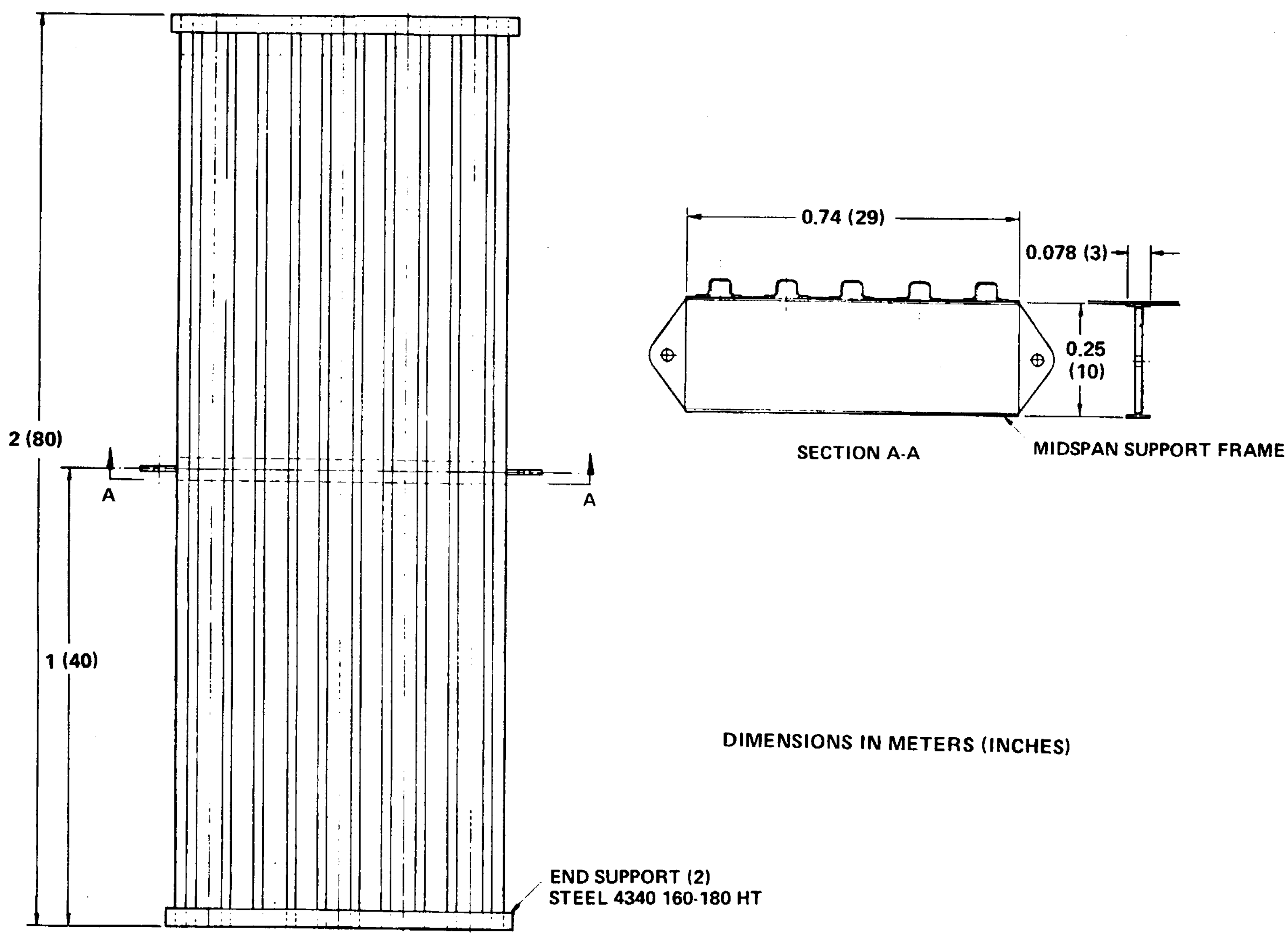
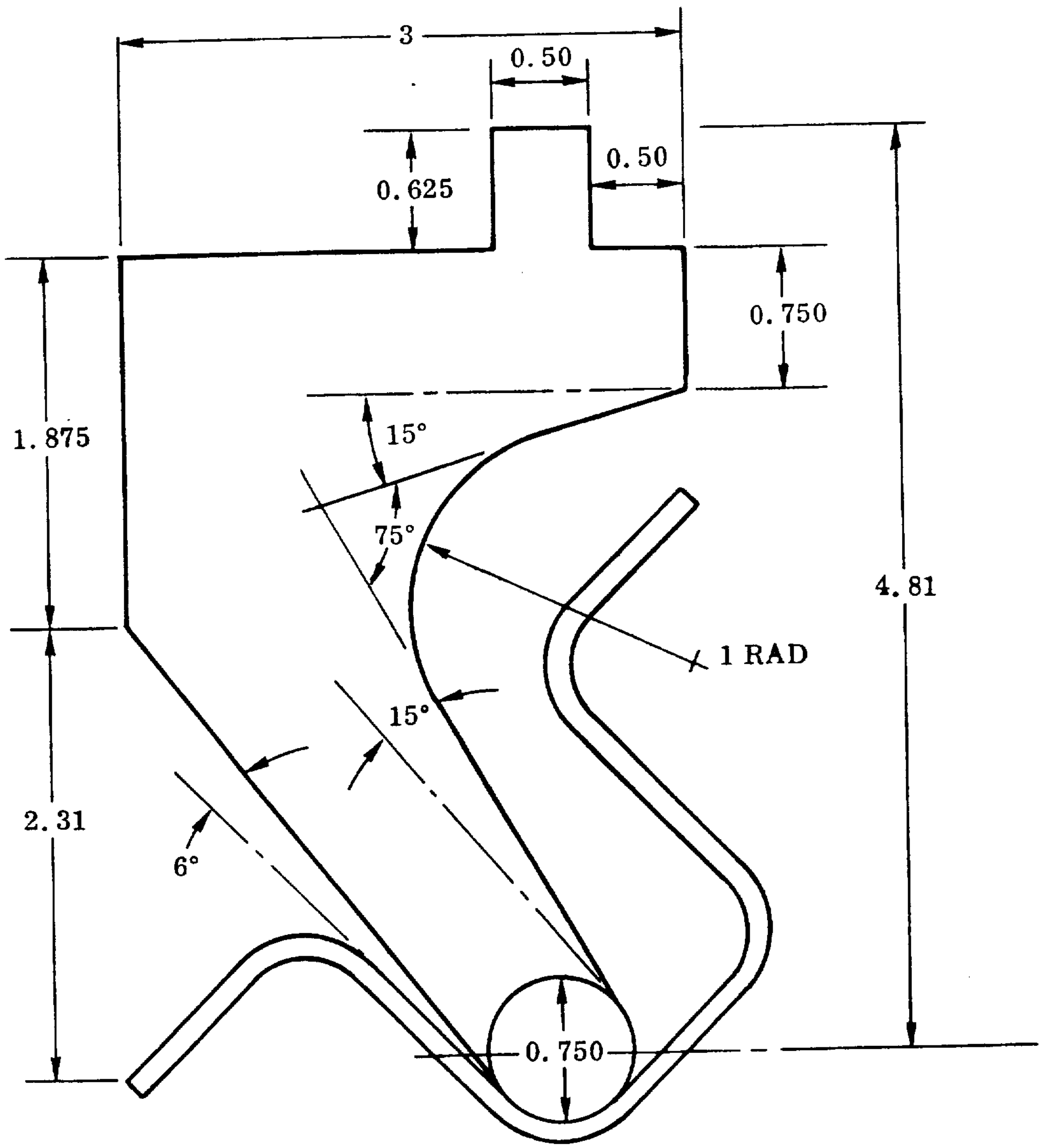


Figure 4-18. Design of the Uniformly Loaded Boron/Aluminum Compression Panel

4.2.2.1 Tooling. A standard goose-neck male punch was required for forming the panel stringers. Because of the length of the hats, a new tool had to be fabricated. A cross-sectional view of the 2.18m (86 in.) long male die used to form the stringers is shown in Figure 4-19.

4.2.2.2 Etching Tanks. Two stainless steel tanks, each 2.3m (90 in.) long, were fabricated from 2 mm (0.080 in.) thick sheet material. One unit was used as a rinse tank while the other served as the etching tank during the fabrication of the Con Clad stringers.



NOTE: FOR CLARITY, UNITS SHOWN ARE INCHES UNLESS OTHERWISE STATED.

Figure 4-19. Male Die Used to Form B/Al Hats

4.2.2.3 End Fittings. The steel end caps for the panel were machined from heat treated 4340 steel. The faces of the caps toward the panel were machined to the configuration shown in Figure 4-20. The grooves were 1.3 cm (0.5 in.) deep and were machined to match the hat sections. The actual slots were not machined until after the stringers had been welded to the skin. This procedure precluded the possibility of any misalignment between a given stringer and the fitting.

4.2.2.4 Titanium Frame. The titanium I-section frame member was fabricated by forming and mechanically fastening titanium sheet material. The finished structure is shown in Figure 4-21.

4.2.2.5 Composite Skin. The material for the 2×0.74m (80×29 in.) skin consisted of one sheet of $(0_3 \pm 45)_s$ B/Al. The skin was trimmed to net size using the diamond disc cutoff saw. Weld schedule and quality control specimens were cut from the trimmed areas.

4.2.2.6 Stringer Fabrication. The stringers for the compression panel were fabricated from Con Clad composite material. Each panel consisted of 0.25 cm (0.1 in.) thick unidirectional B/Al with 0.1 cm (0.040 in.) thick, aluminum clad, mild carbon steel diffusion bonded to each side of the B/Al core. An as-received panel, placed on the cutoff saw prior to trimming, is shown in Figure 4-22.

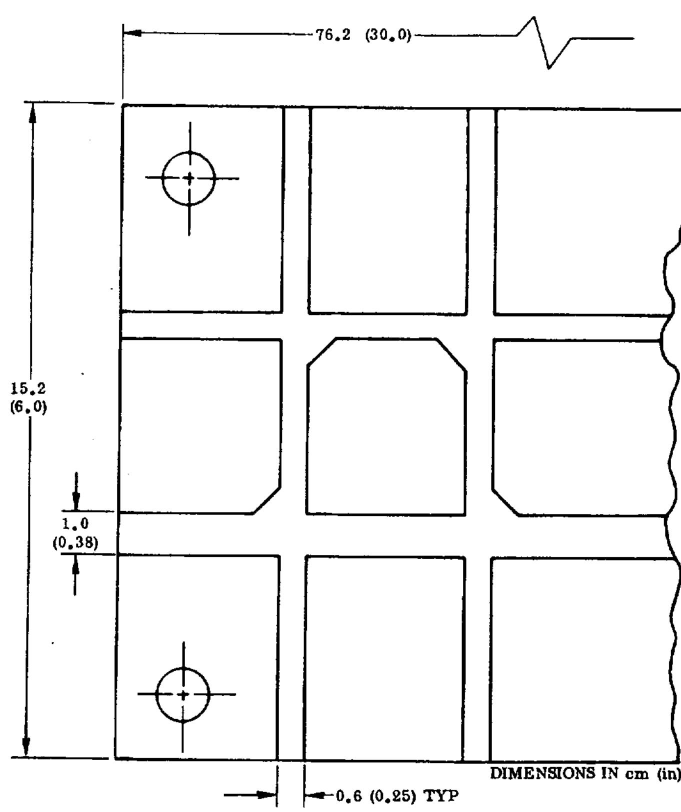


Figure 4-20. Steel End Fitting

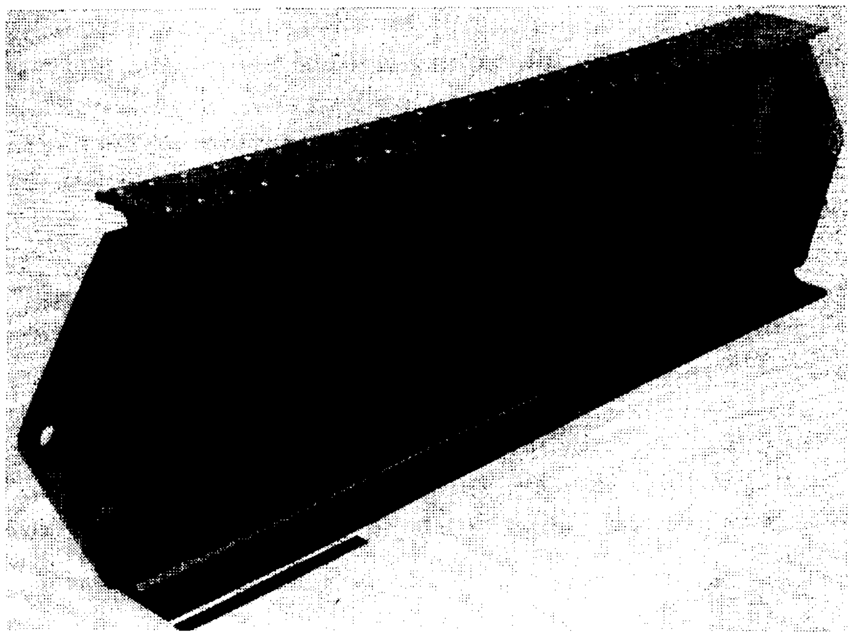


Figure 4-21. Titanium I-Section Frame for the B/Al Compression Panel (131919B)

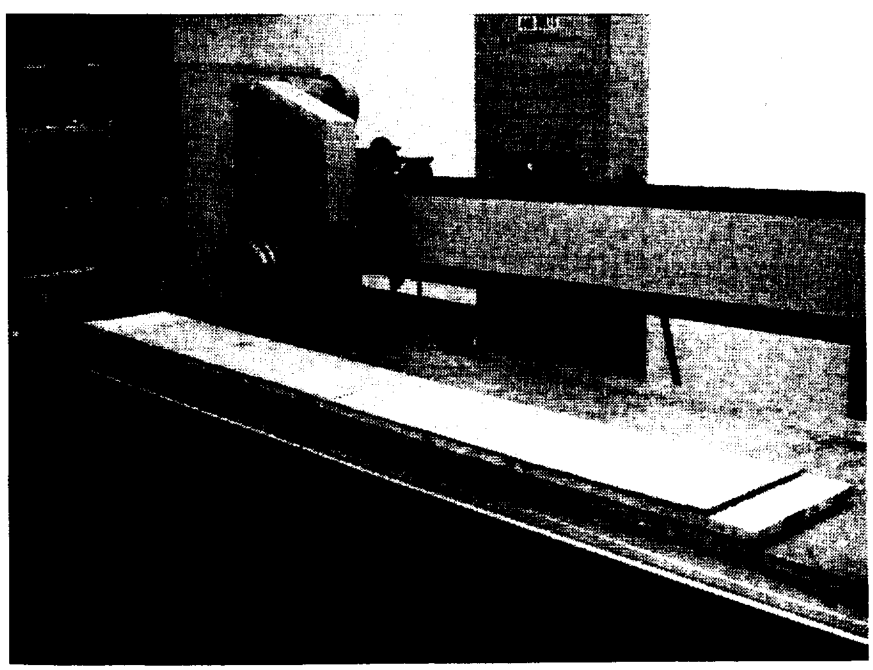


Figure 4-22. Full-Scale Con Clad Panel Ready for Machining (129432B)

Prior to trimming the Con Clad panels, a dummy compression panel was assembled using 6061 Al sheet material. Hat sections were formed from full-thickness aluminum panels; these hats were designed to check out the accuracy of the forming template to be used on the Con Clad panels and to check out the newly fabricated male die punch. No modification of the male punch was necessary; however, the template had to be slightly altered to yield hats with the desired cross section.

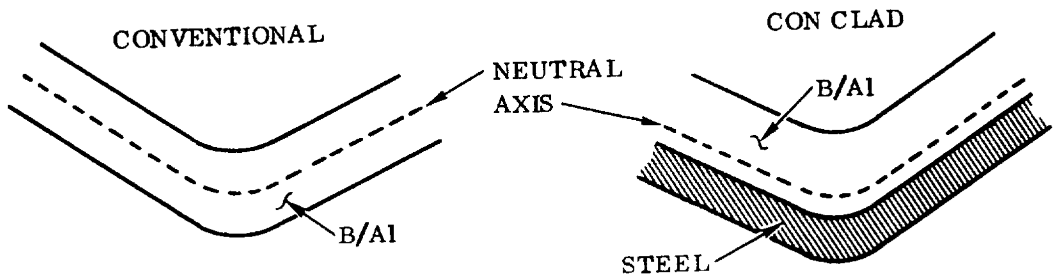
The dummy panel was assembled on a 1.3 cm (0.5 in.) thick aluminum tooling plate and held with aluminum clamps. This plate and the clamps then became part of the bonding fixture used to adhesively bond the steel end fittings to the panel.

After ultrasonic inspection, the Con Clad stringer panels were trimmed to net width on the diamond disc cutoff saw; however, an abrasive cutoff disc was used in place of the diamond wheel because of the lower shearing forces involved in cutting through the steel/composite with the abrasive disc. A roughing cut, approximately 0.6 cm (0.25 in.) deep was made in the upper steel surface of each panel. This cut served to guide the cutoff disc through the material and prevent blade wandering during the final cutting. Several specimens were machined from trimmed areas for weld development and quality control testing. The machining was all performed using a coolant consisting of sulfo-chlorinated oil in Stoddard's solvent.

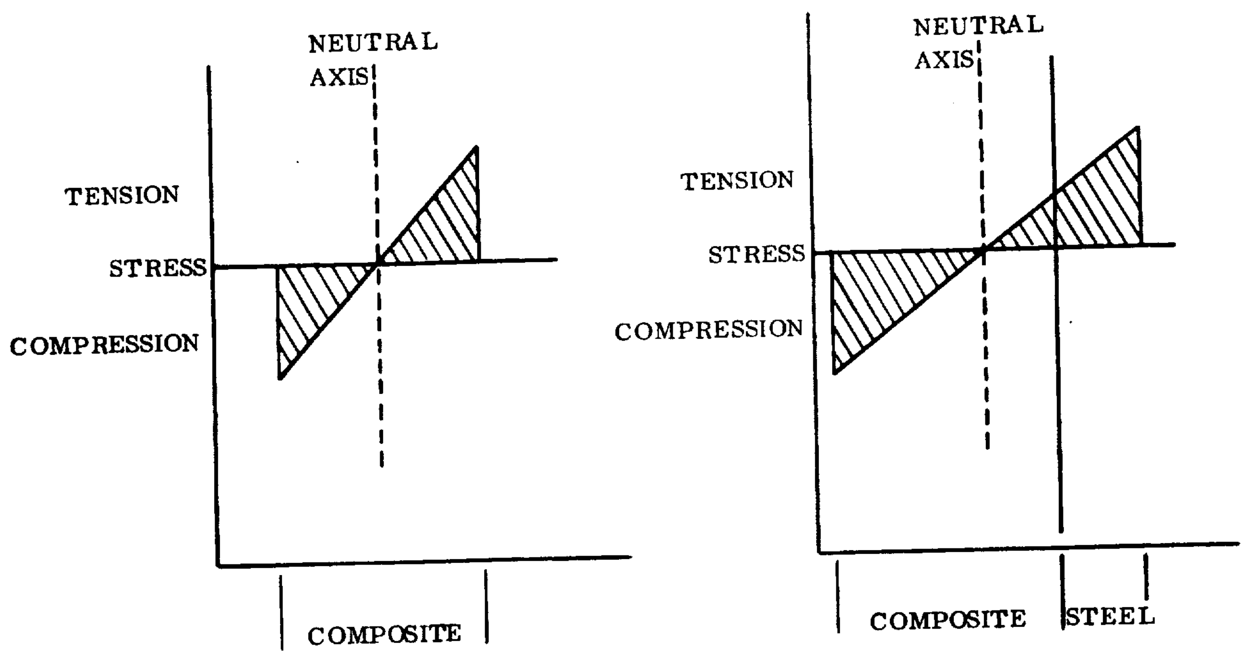
Because of the thickness of the panels, it was necessary to perform selective etching of the steel prior to forming. By removing steel on the compression side of the panel, the neutral axis was shifted in a manner to reduce tension stresses in the composite during forming (Figure 4-23).

Figure 4-24 shows the general sequence of etching used in preparing the stringers. The as-received panels (Figure 4-24a) were sealed around the edges with a chemical maskant and then dipped in a 50% solution of NaOH. This dipping removed the aluminum cladding from the surface of the steel. The panels were then dipped in a chemical maskant (Figure 4-24b) consisting of Turco 552-1. A panel that was just dipped in the maskant is shown in Figure 4-25. The coated panels were then dried in a circulating air furnace for 20 minutes at 355K (180F). After drying, the panels were scribed, and the appropriate amount of maskant stripped (Figure 4-26). The panels were then placed in a tank containing 50% HNO_3. The nitric acid etched the exposed steel, but did not affect material protected by the maskant (Figure 4-24c).

Because of the lower coefficient of thermal expansion of B/Al compared to steel, the composite is put into compression during bonding of the panel and subsequent cool-down. When steel was selectively etched from one side of the panel, that side of the panel was put into tension. Several of the panels with the steel selectively etched off are shown in Figure 4-27. To form the panels, a piece of steel pipe was clamped to the panel (Figure 4-28) until the first two bends were made. At that point, the panel remained straight without any further support.

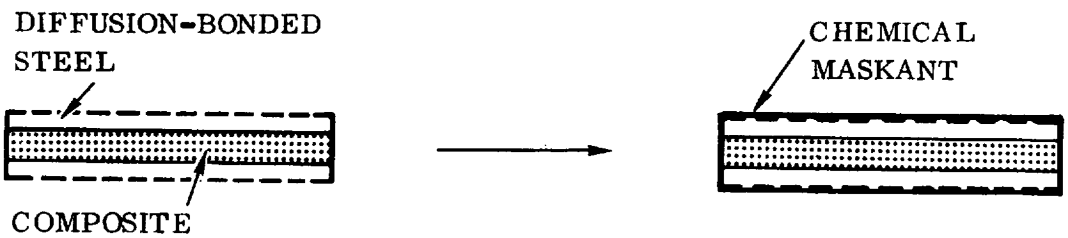


a. Neutral Axis Location



b. Stress Distribution Through Bend

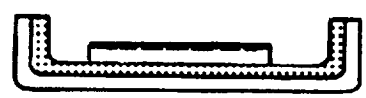
Figure 4-23. Comparison of Conventional Forming and Con Clad Forming with Selective Location of Steel



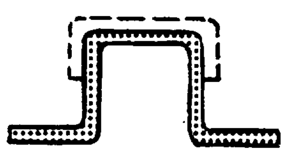
a. As Received.

b. Maskant Application.

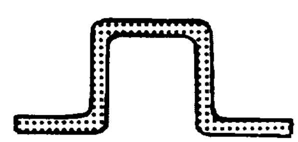
c. Masking Selectively
Removed and
Steel Selectively
Etched Off.



d. Outer Bends Formed.



e. Steel Selectively
Etched Off and
Two Inside Bends Formed.



f. Remaining Steel
Etched Off Leaving
B/Al Hat Section

Figure 4-24. Selectively Placed Con Clad Forming Technique for Hat Sections

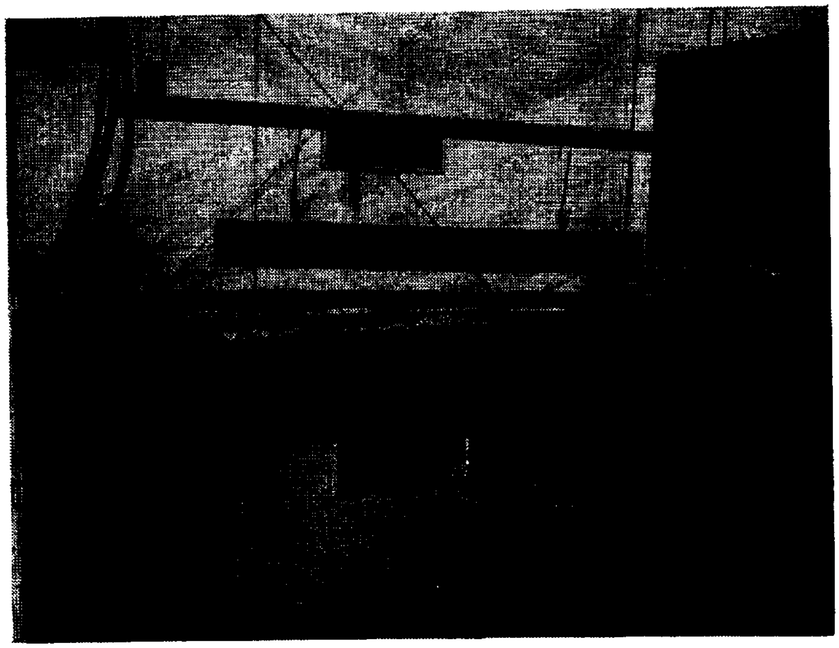


Figure 4-25. Chemically Masking a Con Clad Panel in Turco 552-1 (132507B)

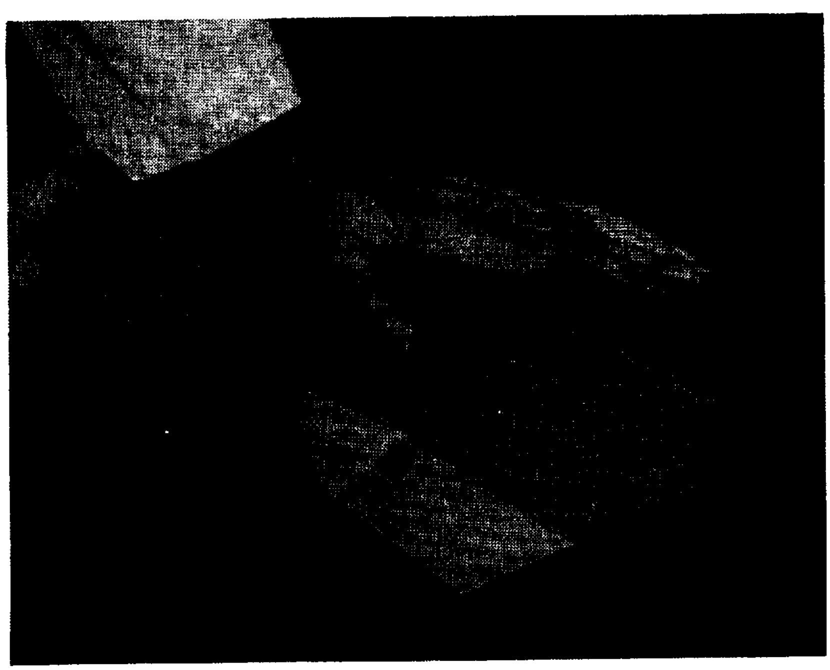


Figure 4-26. Stripping of the Chemical Maskant (132510B)

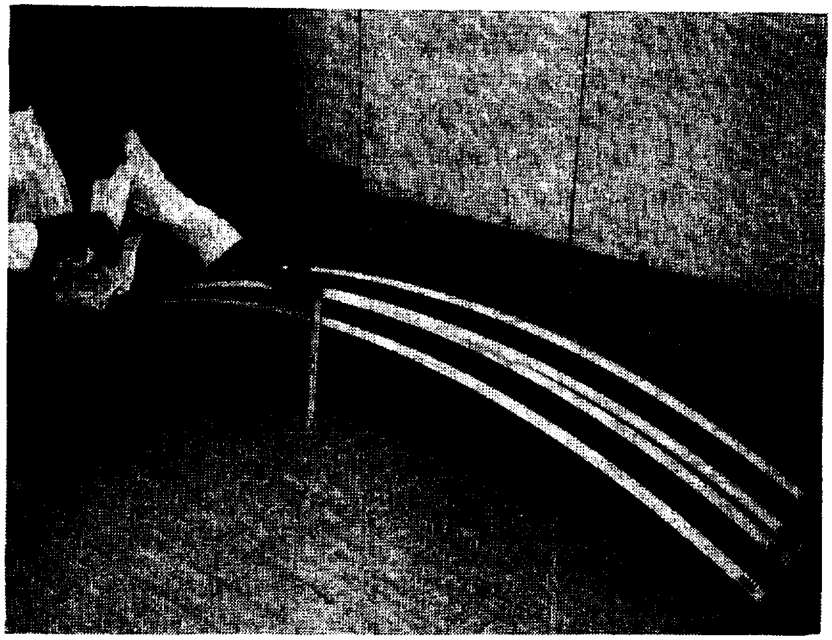


Figure 4-27. Panel Curvature Due to Selective Removal of Steel (132508B)

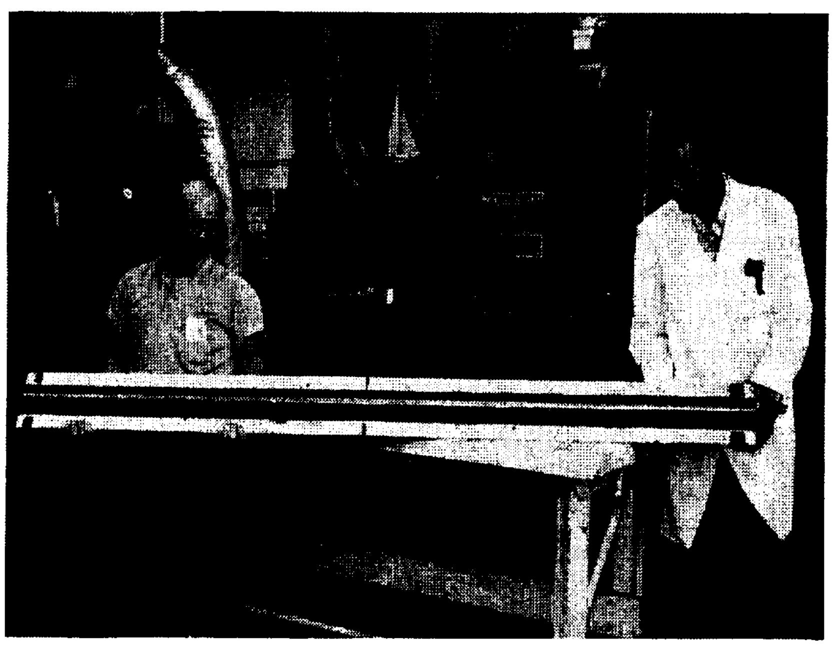


Figure 4-28. Tube Fixture Used to Straighten Panel Prior to Forming (132513B)

The first two bends formed the panel into a U-shaped channel (Figure 4-24d). The chemical maskant was then removed from the steel on the outside of the channel, and the steel chemically removed in HNO_3. The final two bends were then made to form the hat (Figure 4-24e). All hats were cold formed on a 16-foot Cincinnati brake press. One hat that was just formed is shown in Figure 4-29. After forming, the remaining steel was etched off the panel (Figure 4-24f). A hat section being dipped into the etching tank prior to final steel removal is shown in Figure 4-30. A completed hat section after etching is shown in Figure 4-31. The 2m (80 in.) long, 0.24 cm (0.1 in.) thick, hat is shown with the brake press used for forming, in the background. After forming, the panels were trimmed to net size in preparation for resistance welding.

4.2.2.7 Panel Assembly. Four holes were punched in each stringer (two at each end) for alignment during welding. The weld development schedules were previously prepared and the results are reported in Section 3. During actual panel welding, the weld schedule was slightly modified by increasing the weld heat input. The same welding stands used in fabricating the shear beam were used to support the compression panel. Aluminum clamps from the bonding fixture were used to keep the panel flat during welding. Welding proceeded from the middle of the panel towards the ends. Approximately 10 welds were made on each side of the center stringer, and then the other stringers were welded over a similar distance (working from the center of the panel towards the edge). By following this procedure, there was almost no distortion in the panel after performing the 840 spot welds.

4.2.2.8 Nondestructive Evaluation. After welding, the panel was ultrasonically inspected. The C-scans indicated that all welds were satisfactory with only three welds showing less than a 100% bond.

4.2.2.9 Final Machining and Bonding. After ultrasonic inspection the ends of the panel were ground flat and parallel. Because of the size of the panel, milling was performed on a three-axis Giddings-Lewis NC machine (Figure 4-32). Milling was performed using a 3.8 cm (1.5 in.) diameter, 7.6 cm (3 in.) high router plated with 40-60 grit diamonds. A spindle speed of 190 rpm at a feed rate of 7.9 cm/min (3.12 in/min) was used. Two passes were made to remove a total of 0.1 cm (0.05 in.) from each end of the panel. The finishing pass, removing only 0.01 cm (0.005 in.), brought panel ends parallel within 0.002 cm (0.0007 in.). A spray mist coolant was used during all machining.

After the panel was milled flat and parallel, the slots in the steel end fittings were machined and the panel assembled in the aluminum bonding fixture. Threaded steel rods were inserted along the axis of each hat and through holes in the steel fittings. These rods were then bolted to keep the fitting in place prior to bonding.

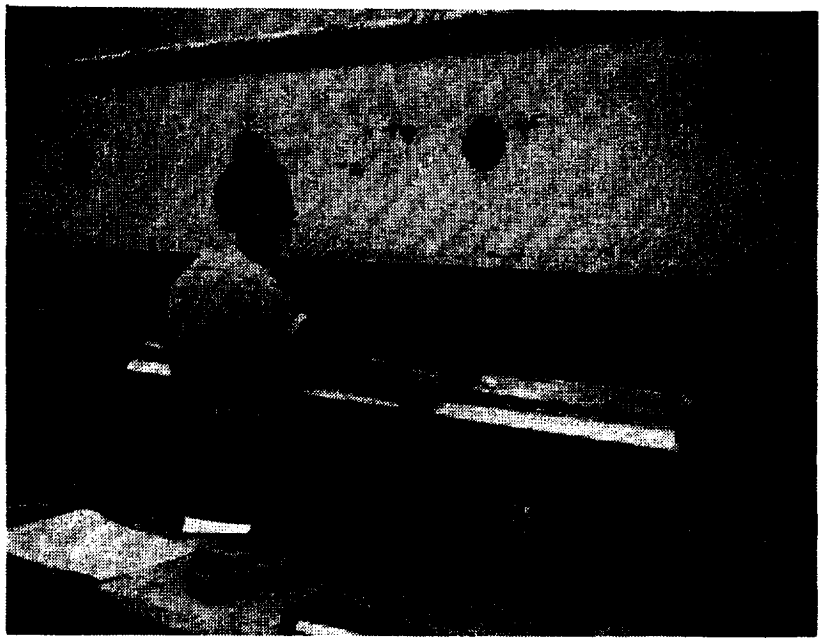


Figure 4-29. Forming a 2m (80 In.) Hat Section (132512B)

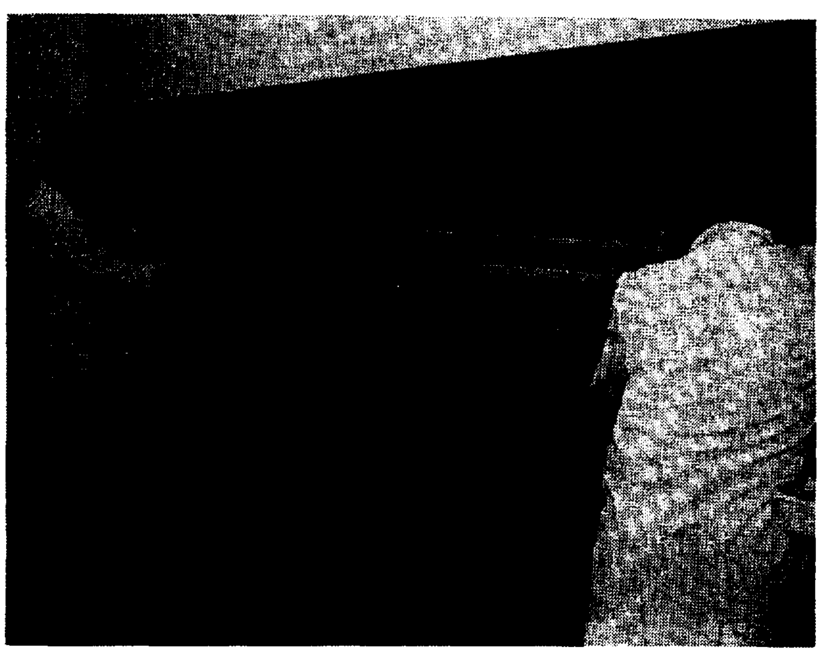


Figure 4-30. Final Etching of Con Clad Hat (132509B)

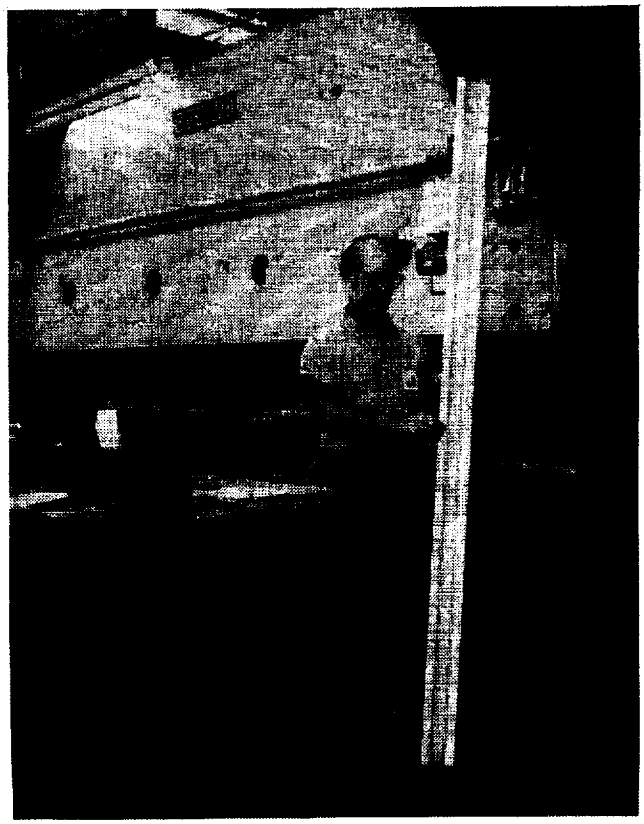


Figure 4-31. Finished 0.24 cm (0.1 In.) Thick, 2m (80 In.) Long B/Al Hat Section (132511B)

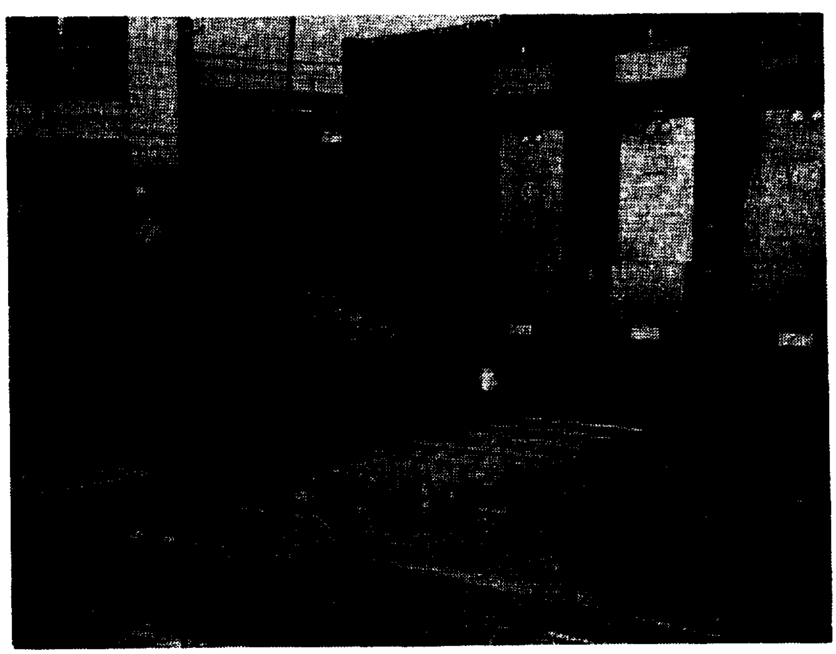


Figure 4-32. End Milling the B/Al Compression Panel (132836B)

Standard procedures developed at Convair Aerospace were used to pot the B/Al panel into the steel end fittings. The fittings were first removed from the panel and grit blasted to remove scale, then solvent wiped. A thin (0.003 cm, 0.0012 in.) wet coat of Bloomingdale BR-34 polyimide primer was then painted onto those areas to be potted. The fittings were dried 30 minutes at 450K (350F) in a vented, circulating-air oven. The sections of the B/Al panel to be potted were lightly abraided and solvent wiped. A coating of Pasa Jel 105 was next painted on, allowed to stand 10 minutes, and rinsed clean. After the end caps were reassembled onto the panel, Hexcel 901 foam was used to pot the panel into the blocks, with the foam filling approximately two-thirds of the potting cavity and in intimate contact with the B/Al surface. The entire panel and bonding fixture were then bagged and vacuum was maintained. The bagged assembly was then cured and post cured according to the schedule in Table 4-7.

Table 4-7. Curing Procedure for the B/Al Compression Panel

I Cure Cycle

- a. Apply full vacuum, to be maintained for the entire run.
- b. Heat at 0.5 to 1K/min (1 to 2 F/min) to 338K (150F).
- c. Heat at 1.7 to 2.2K (3 to 4F) to 450K (350F).
- d. Hold at 450K (350F) for 90 minutes.
- e. Cool at 1K/min (2F/min) to below 338K (150F) before releasing vacuum.

II Post Cure

- a. Strip off all bagging material and sealant. No burnable material can remain.
- b. Heat in an oven at 1 to 2K/min (2 to 5F/min) to 533K (500F).
- c. Hold at 533K (500F) for 1 hour.
- d. Heat at 1 to 2K/min (2 to 5F/min) to 589K (600F).
- e. Hold at 589K (600F) for 2 hours.
- f. Cool at 1K/min (2F/min) to below 338K (150F).

4.2.2.10 Final Assembly. After post curing, the titanium I-frame was mechanically fastened to the panel. The holes in the panel were formed by punching with a tool similar to that described in Section 4.1. The front and back of the finished compression panel are shown in Figures 4-33 and 4-34. After final assembly the panel was packed for shipment to NASA-MSFC.

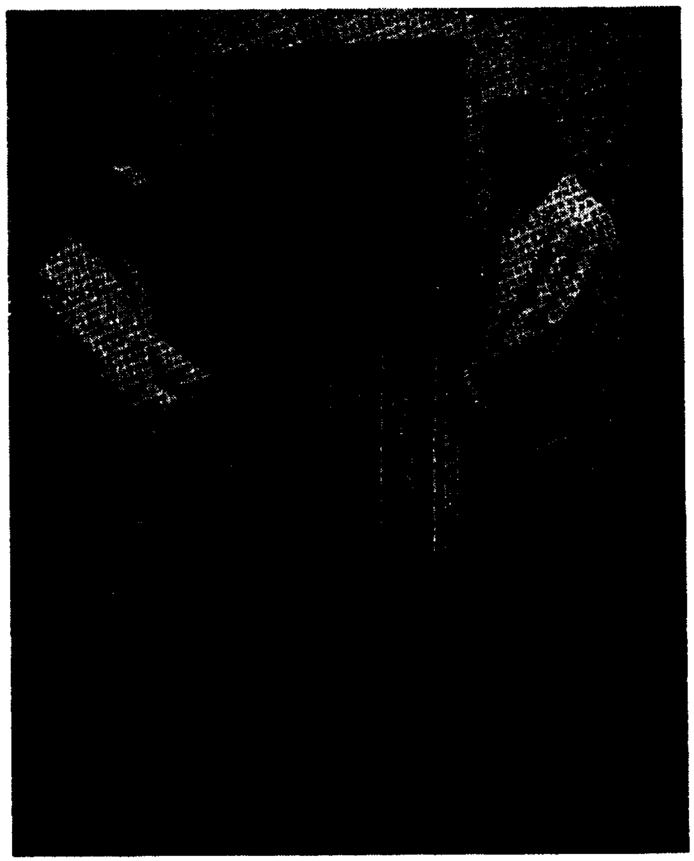


Figure 4-33. Front of Completed B/Al Compression Panel (133438B)

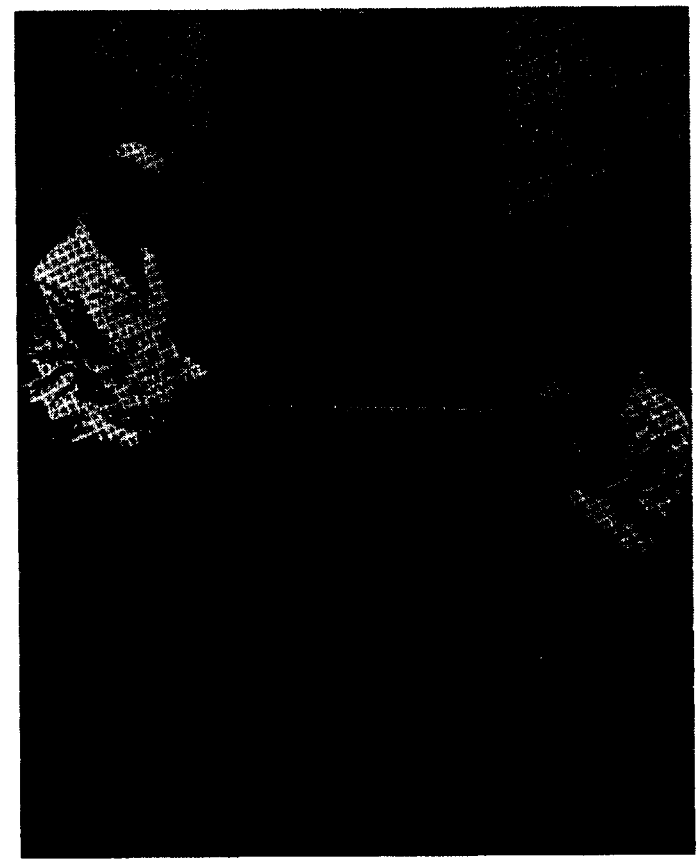


Figure 4-34. Rear of Completed B/Al Compression Panel Showing the I-Section Frame (133439B)

4.2.2.11 Cost Analysis. No rigorous cost analysis was performed during the program; however, it is possible to determine the approximate cost of fabricating the compression panel. For this purpose, all development costs (including weld schedule development), test fitting costs, bonding costs, and costs for the titanium frame have been eliminated. The final cost for the panel (including nonrecurring costs such as tooling) was $34,800. Material costs were $19,000, and the trimmed panel weight (composite only) was 20.2 kg (44.4 lb). Therefore, the panel cost was $1740/kg ($790/lb) including nonrecurring costs. Total tooling costs were $4400; consequently, the total panel cost (excluding nonrecurring costs) was $30,400 or $1510/kg ($690/lb).

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

Based on the work performed on this program and presented in Volumes I and II, the following conclusions and recommendations are made.

5.1 DESIGN AND ANALYSIS

1. Four large, heavily loaded, structural segments of the space shuttle booster section were designed utilizing boron/aluminum (B/Al). The adequacy of these designs was then proved by analysis. The successful design and analyses of these large, complex structures increases the confidence level in the use of this advanced composite material.
2. Subelements representative of sections of the booster structure were successfully designed, analyzed, fabricated and structurally tested thus demonstrating the adequacy of the design and analysis of B/Al structures.
3. Compression flight hardware structures made from B/Al may now be designed with a high degree of confidence for usage up to 589K (600F). This is due to the advancement of the state-of-the-art of crippling analysis methods for unidirectional B/Al, that was accomplished at Convair Aerospace prior to and during the present program.
4. It is recommended that crippling analysis methods be developed for B/Al crossply materials, to be used primarily in skins and joints.
5. The nonlinear behavior of B/Al crossply material made it necessary to use some nonlinear analytical methods for the shear beam web. Biaxial stress-strain data was not available; consequently, it became necessary to use secant moduli and Poisson's ratio data from uniaxial stress-strain curves to approximate them.
6. It is recommended that biaxial stress-strain and stress-Poisson ratio curves be generated for crossply B/Al composites for use in future flight hardware design and analysis tasks.

5.2 MATERIAL PROPERTY TESTING

1. Mechanical properties were determined on unidirectional and crossplied B/Al at room and elevated temperatures. Typical longitudinal tensile strengths of 1289 MN/m^2 (216 ksi) were obtained.
2. A statistical analysis was performed on the mechanical property data to provide design allowables. Additional testing is required to provide a large data base and increase confidence levels.

3. The effects of heat treatments on the mechanical properties of B/Al were determined. Maximum improvements in strength and modulus were obtained with a solution treat plus cryogenic soak plus aging treatment.

4. A test program was performed to determine the susceptibility of B/Al to corrosion and to evaluate a number of corrosion protection systems for use in low- and high-temperature environments. Both acrylic and polyurethane coating systems provided adequate corrosion protection at moderately elevated temperatures [366K (200F)]. A chromic acid anodizing process provided the best protection at high temperatures [589K (600F)]; however, additional testing at high temperatures is recommended.

5. Quality assurance (nondestructive and mechanical property testing) indicated that the B/Al material received on this program [64 panels weighing in excess of 137 kg (300 lb)] was consistently of high quality. All material was received on schedule.

5.3 PROCESS DEVELOPMENT

5.3.1 MACHINING. The use of a diamond disc cutoff saw to machine large, thick B/Al sections was demonstrated. The saw was used to trim sections over 1.5 cm (0.6 in.) thick, with the cut surface sufficiently smooth to permit subsequent fabrication without further machining. The average wheel loss was 2×10^{-5} m/m for B/Al material in the as-received condition; however, wheel loss doubled for heat treated material.

The rotary ultrasonic machine was found to be satisfactory for drilling thick B/Al over 0.3 cm (0.1 in.) thick, heat treated B/Al, and B/Al joined to conventional materials such as steel and titanium. Hole punching techniques followed by reaming with a diamond-plated twist drill produced excellent quality holes in B/Al under 0.3 cm (0.1 in.) thick.

Additional development of the hole punching process could result in an increase in the material thicknesses that can be processed by this technique.

5.3.2 CON BRAZ JOINING. The method and applicability of Con Braz joining was demonstrated on the program. Over 24.5 m (80 ft) of I-sections were successfully Con Braz joined using a semi-automated joining module. While brazing alloys for applications up to 393K (250F) are available, additional work must be performed to develop alloys suitable for 589K (600F) application. Additional work must also be performed to develop proper joining techniques for thick gage [1.3 cm (0.5 in.) thick and greater] B/Al. Thermal cycling Con Braz joined structures (B/Al to B/Al and B/Al to Ti) between 77K (-320F) and 366K (200F) has no detrimental effect on joint properties.

5.3.3 RESISTANCE WELDING AND RESISTANCE JOINING. Resistance welding and resistance joining proved satisfactory for joining multiple sheets of B/Al and Ti in thicknesses up to 1.5 cm (0.6 in.). Joint efficiencies from 60 to 100% were obtained at room temperature; these values were not affected by thermal cycling. Over 50% of joint strength was retained at 589K (600F).

5.3.4 PLATING. Both electroless and electrolytic brush plating were successfully incorporated into B/Al fabrication. The electroless process yielded slightly higher joint strengths, while the brush plating was more convenient for in situ plating where immersing in a bath was undesirable.

5.3.5 CON CLAD FORMING. Room temperature forming of B/Al sheets up to 2m (80 in.) in length and 0.3 cm (0.1 in.) in thickness was performed on standard shop brake presses when mild carbon steel was clad to the composite surface prior to forming. The cladding may impart some residual tensile stresses into the composite panel. Further investigations to determine the extent of these residual stresses are recommended to permit even greater utilization of this forming process.

5.4 COMPONENT FABRICATION

Two selected components utilizing the processes examined on this program were fabricated.

5.4.1 SHEAR BEAM COMPONENT. A 1 by 0.96m (40 by 38 in.) shear resistant shear web beam was fabricated and shipped to NASA-MSFC for testing at room temperature.

5.4.1.1 Shear Beam Elements. The shear beam consisted of 21 vertical and horizontal I-section stiffeners fabricated by Con Braz joining. The heat treated web was spliced together by resistance welding. A compression cap that tapered in thickness was attached to the web with mechanical fasteners and by resistance joining. The stiffeners were attached to the web by resistance welding and tied to each other (at intersection joints) with mechanical fasteners.

5.4.1.2 Shear Beam Cost and Weight. The final weight of the shear beam component was 35.4 kg (78 lb), and the total cost, excluding tooling, was $66,700 or $1880/kg ($855/lb). Tooling costs amounted to $11,000, and therefore the cost of the shear beam, including nonrecurring items was $78,000, or $2060/kg ($940/lb).

5.4.2 COMPRESSION PANEL COMPONENT. A 2 by 0.75m (80 by 29 in.) compression panel was fabricated and shipped to NASA-MSFC for testing at 589K (600F).

5.4.2.1 Compression Panel Elements. The compression panel consisted of a single crossplied skin with five Con Clad formed stringers running the full 2m (80 in.) length. The stringers were resistance welded to the panel. A titanium frame was mechanically fastened to the rear of the panel 1m (40 in.) from each end.

5.4.2.2 Compression Panel Cost and Weight. The final weight of the compression panel was 20.2 kg (44.4 lb), and the total cost, excluding tooling was \$30,400, or \$1510/kg (\$690/lb). Tooling costs amounted to \$4400; therefore, the cost of the compression panel, including nonrecurring items was \$34,800 or \$1790/kg (\$790/lb).

5.4.3 B/Al STRUCTURES. This program demonstrated that B/Al structures can be designed and fabricated for representative structural assemblies having high load intensities. The fabrication can be accomplished with today's technology and existing shop equipment and personnel. Using sheet metal fabrication techniques, these composites structures can be fabricated at reasonable cost.

SECTION 6

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APPENDIX A

SPECIFICATIONS

This appendix contains one material and three process specifications. They are: Specification 0-00854, Specification for Composite Material; Specification 0-73540, Sawing of Boron/Aluminum Composite; Specification 0-73540, Drilling of Boron/Aluminum Composite; and Specification 0-73541, Con Braz Joining of Boron/Aluminum Composites.

A. SPECIFICATION FOR COMPOSITE MATERIAL

All composite material for the current program was purchased to Convair Aerospace Specification 0-00854 for boron/aluminum sheet material.

Sheet, Composite, Boron Filament,
Aluminum Alloy Specification for

PRELIMINARY

1. SCOPE

1.1 Scope. This specification establishes the requirements for a composite boron filament aluminum alloy material.

1.2 Classification. The material covered by this specification shall be classified in the following types and grades.

Type I unidirectional plies (filament)

Type II cross plies (filament)

Grade A - 25.00 ± 1.25 percent boron filament by volume

Grade B - 37.50 ± 1.25 percent boron filament by volume

Grade C - 50.0 ± 0 percent boron filament by volume

Grade D - 45.0 ± 1.25 percent boron filament by volume

1.3 Classification identification. For classification of the material covered by this specification see 6.3.

2. APPLICABLE DOCUMENTS

2.1 Unless otherwise specified below, the following documents of the issue in effect on date of Convair's request for quotation form a part of this specification to the extent specified.

SPECIFICATIONS

Federal

QQ-A-250	Aluminum and Aluminum Alloy Plate and Sheet; General Specification For

Society of Automotive Engineers

AMS 36CH (Draft)	Filaments, Boron

STANDARDS

Federal

FTMS No. 151, Method 211.1	Metals; Test Methods
Fed. Std. No. 245	Tolerances for Aluminum Alloy and Magnesium Alloy Wrought Parts

3. REQUIREMENTS

3.1 Material. The material shall be furnished as composite flat sheet formed by diffusion bonding of boron filaments and aluminum alloy in such manner the filaments are solidly embedded in an aluminum alloy matrix.

3.1.1 Boron filament. The boron filaments shall be of the diameter specified on the contract or purchase order and shall meet all the requirements of Specification AMS 36CH (Draft).

3.1.2 Aluminum alloy. The aluminum alloy shall be 6061-F unless otherwise specified on the contract or purchase order and shall meet all the requirements of Federal Specification QQ-A-250d.

3.1.3 Filament alignment. All filaments comprising a single ply shall be laid parallel one to another within one degree of the long axis of the ply.

3.1.4 Plies. The longitudinal direction of each ply used in compositing the material as related to the long axis of the sheet shall be as specified on the contract or purchase order.

3.2 Physical properties. The material shall meet the requirements of Table I.

Table I
Physical Properties (at room temperature)
Minimum Values

Material Type and Grade	Tensile Strength Long.	Tensile Strength Trans.	Modulus of Elasticity
Type I			
Grade A, psi	75,000	12,000	16×10^6
Grade B, psi	115,000	12,000	24×10^6
Grade C, psi	160,000	12,000	32×10^6
Type II (0-90° CP)			
Grade D, psi	65,000	60,000	19×10^6

3.3 Dimensions. The composite sheet shall be furnished in the thickness and size as specified on the contract or purchase order.

3.3.1 Tolerances. Tolerances, unless otherwise specified, shall be as specified in Federal Standard No. 245c.

3.4 Finish. Unless otherwise specified on the contract or purchase order the material shall be furnished in the mill finish.

3.5 Surface defects. The surface shall be free from cracks, scratches, folds, wrinkles, laps, indentions, edge delaminations, foreign objects, or other defects which would adversely affect the serviceability of the material. If the surface defects can be removed, and the required section thickness be maintained, the defects shall not be cause for rejection. Under no conditions are cracks or edge delamination permissible.

3.6 Internal defects. The material shall be free from voids, delaminations, stray filaments, broken filaments, filament and ply misalignment, and foreign matter. (See Figures 1 through 11.)

3.7 Boron filament percent by volume. Material percentage of boron filament content by volume shall be in accordance to grade as specified herin.

3.8 Product markings. The material shall be legibly identified with the following information.

a. 0-00854 and applicable dash number.
b. Purchase order number.
c. Manufacturer's name.
d. Alloy and temper as applicable.
e. Size of material.
f. Lot number.

The marking material shall be such as to resist obliteration during normal handling and shall be removable by normal cleaning methods; however ghost images of the characters may remain. Markings shall appear at each end of the material.

3.9 Workmanship. The material shall be of uniform quality and condition, free from protruding filament ends and burrs.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for inspection and test. Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection and test requirements as specified herein. Except as otherwise specified, the supplier may use his own facilities or any commercial laboratory acceptable to Convair. Convair reserves the right to perform any or all of the inspections set forth herein where such inspections are deemed necessary to assure that the material to be furnished conforms to the prescribed requirements.

4.2 Inspection records. Inspection records of examinations and tests shall be kept complete and available to Convair. These records shall contain all data necessary to determine compliance with the requirements of this specification.

4.3 Classification of examinations and tests. The examinations and tests of the material shall be classified as follows:

a. Qualification verification
b. Acceptance verification
c. Receiving inspection

4.3.1 Qualification verification. Qualification verification shall consist of all the examinations and tests specified herein.

4.3.2 Acceptance verification. Acceptance verification shall be performed on representative samples of each lot of material, and shall consist of the following:

a. Examination of product
b. Tensile strength
c. Modulus of elasticity

4.3.3 Receiving inspection (for Convair only). Receiving inspection shall consist of an examination of the material and such sampling and verification of test data as deemed necessary.

4.4 Sampling plan.

4.4.1 Quality assurance sample. A quality assurance sample shall be selected at random from the production lot submitted for acceptance by Convair at any one time, and furnished to Convair at time of lot submittal.

4.4.2 Quality assurance sample rejection. If any specimen of the quality assurance sample fails any inspection or test specified herein, the entire lot represented by the sample shall be rejected.

4.4.3 Lot definition. A lot shall consist of all material of similar composition and size and completely processed in the same manner.

4.5 Test conditions. Test conditions shall be as specified in 4.6.

4.6 Test methods.

4.6.1 Examination of product. The material shall be examined to verify that the markings, size, surface, and workmanship conform to the requirements of this specification.

4.6.2 Tensile strength and modulus of elasticity. Compliance with the requirements of 3.2, Table I shall be determined in accordance with Federal Test Method Standard No. 151a, Method 211.1.

4.6.3 Internal defects. Compliance with the requirements of 3.6 shall be determined by inspections, tests and methods agreed upon by Convair and Vendor.

4.6.4 Boron filament percent by volume. Compliance with the requirements of 3.7 shall be determined by an inspection method agreed upon by Convair and Vendor.

5. PREPARATION FOR DELIVERY

5.1 Preservation and packaging. Preservation and packaging of all material furnished under this specification shall be sufficient to afford adequate protection against corrosion and physical damage during handling, shipping, and storage. Each package or container shall contain only material from the same lot.

5.2 Packing. The material shall be packaged as specified in 5.1 and packed in a manner which will ensure acceptance by common carrier at lowest rates and will ensure protection against damage during shipment.

5.3 Marking for shipment. Each shipping container shall be identified with lable, tag, or marking which includes the following data.

a. 0-00854 and applicable dash number.
b. Purchase order number.
c. Manufacturer's name.
d. Material description.
e. Quantity and unit size.
f. Lot number.
g. Precautionary, handling, and storing warnings, as applicable.

6. NOTES

6.1 Intended use. The material covered by this specification is intended to be used in the manufacture of structural components when the composite properties of high modulus filament and aluminum alloy matrix are desirable. Use is not restricted to this application.

6.2 Ordering information. The following information should be included on the purchase order.

a. Number, title, and date of this specification.
b. Filament diameter.
c. Alloy and temper.
d. Lay of plies.
e. Size and thickness of composite sheet.
f. Quantity.

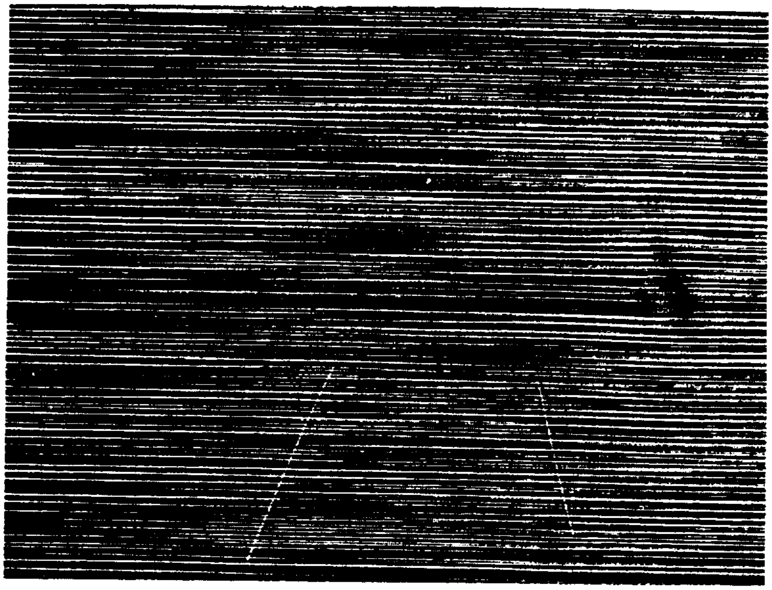
6.3 Material classification identification. The classification identification numbers for the material specified herein shall consist of the number of this specification and the applicable dash number as given below:

Type	Grade	Convair Designation
I	A	0-00854-1
I	B	0-00854-2
I	C	0-00854-3
II	A	0-00854-4
II	B	0-00854-5
II	C	0-00854-6
II	D	0-00854-7

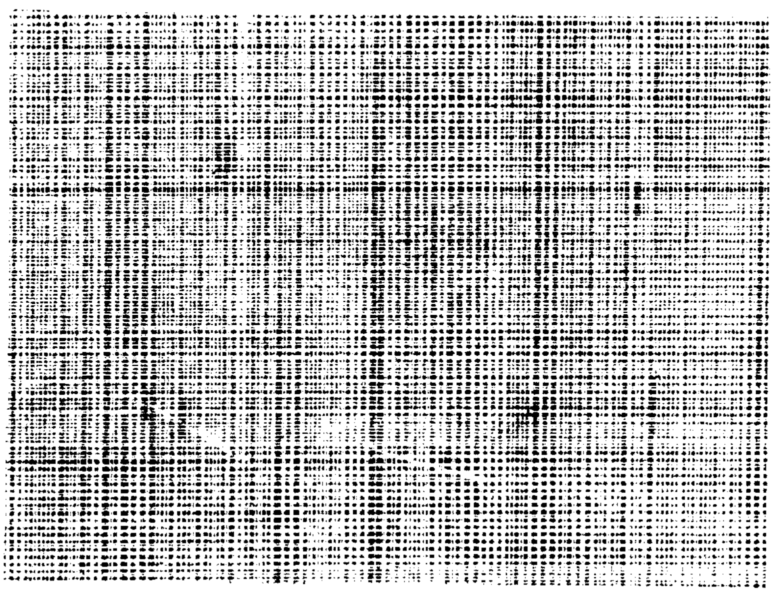
6.4 Approved sources. The approved sources for the material described by this specification are:

Manufacturer's Name and Address	Type	Grade	Convair Designation
(To be determined)			

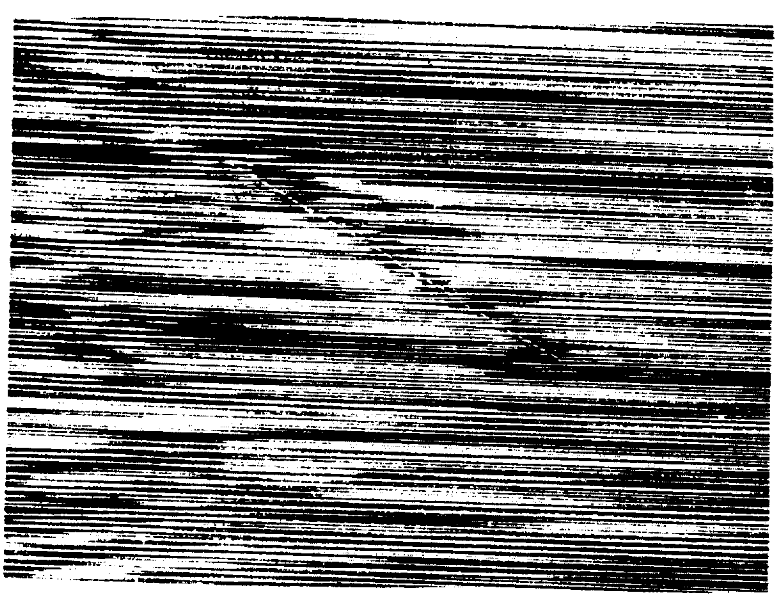
Figure 1. Stray Boron Filaments. (Radiographs enlarged 8X.)



a. Unidirectional layup. (Note deformation of horizontal filaments surrounding strays.)

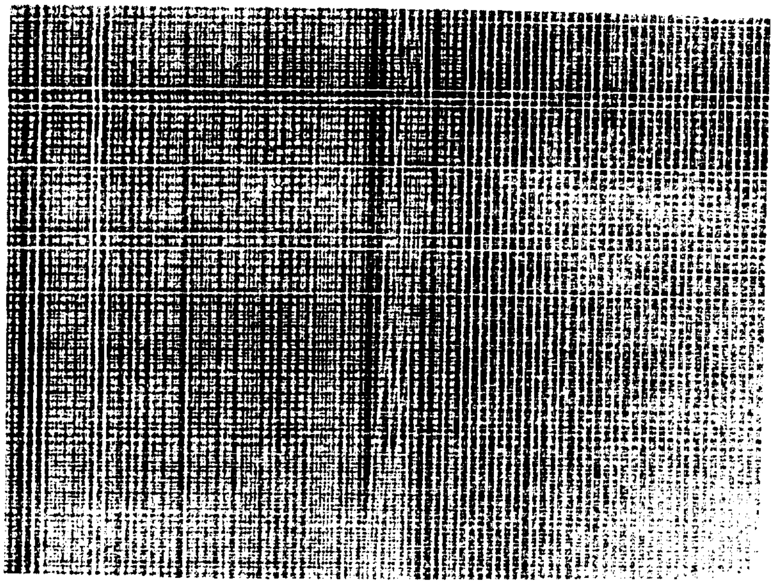


b. Zero to 90 crossply layup. (Note vertical filament breakage attendant with the stray filaments.)



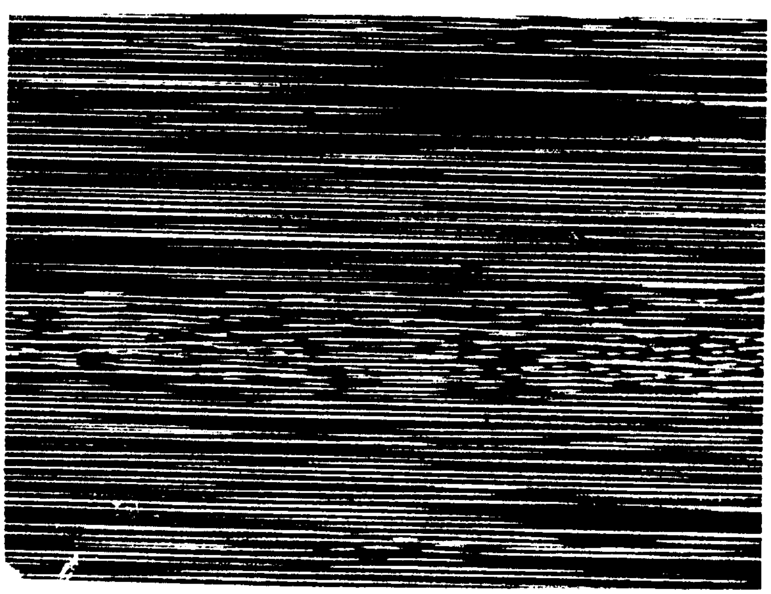
c. Unidirectional layup. (Note deformation and breakage surrounding the stray.)

Figure 2. Crossed-over Filaments. (Radiographs enlarged 8X.)



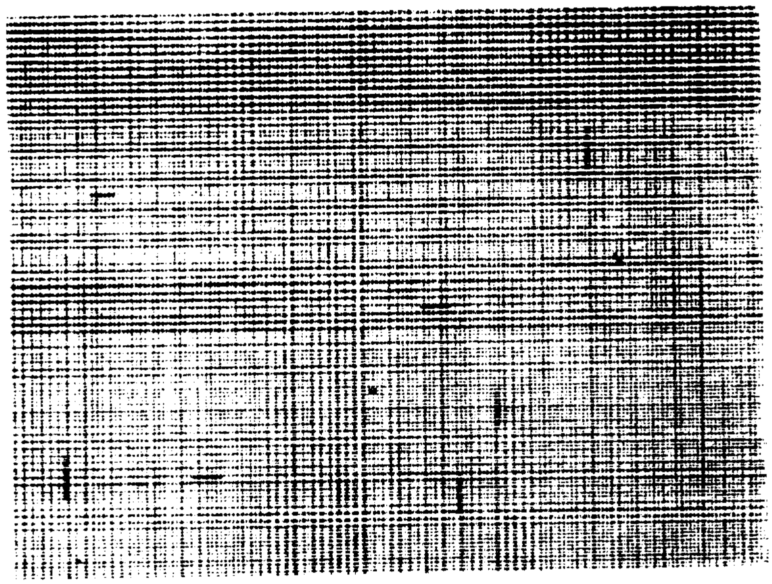
a. Zero to 90 crossply layup. (Note resultant spacing irregularity and minor horizontal filament breakage)

b. Zero to 90 crossply layup. (Note resultant moderate vertical filament breakage.)

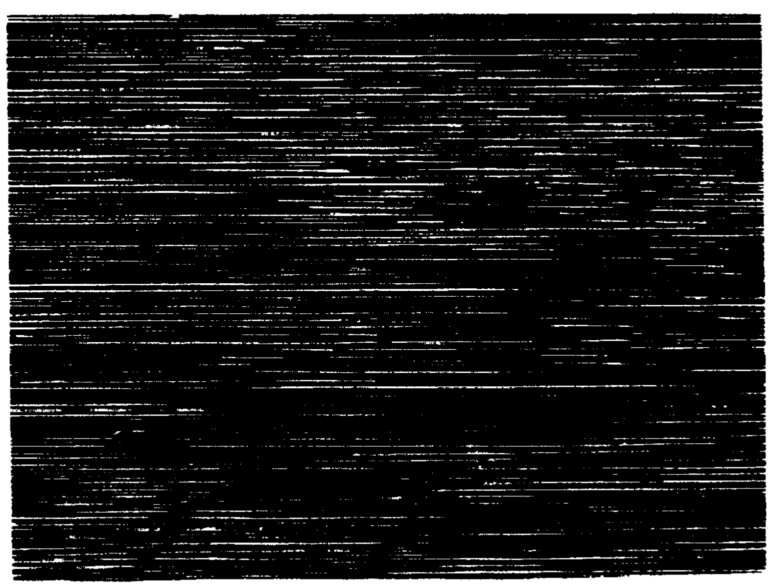


c. Unidirectional layup. (Note no attendant breakage apparent.)

Figure 3. Random Filament Breakage.
(Radiographs enlarged 8X.)



a. Zero to 90 crossply layup. Separation up to 0.030 inch.



b. Unidirectional layup. Separation up to 0.007 inch.

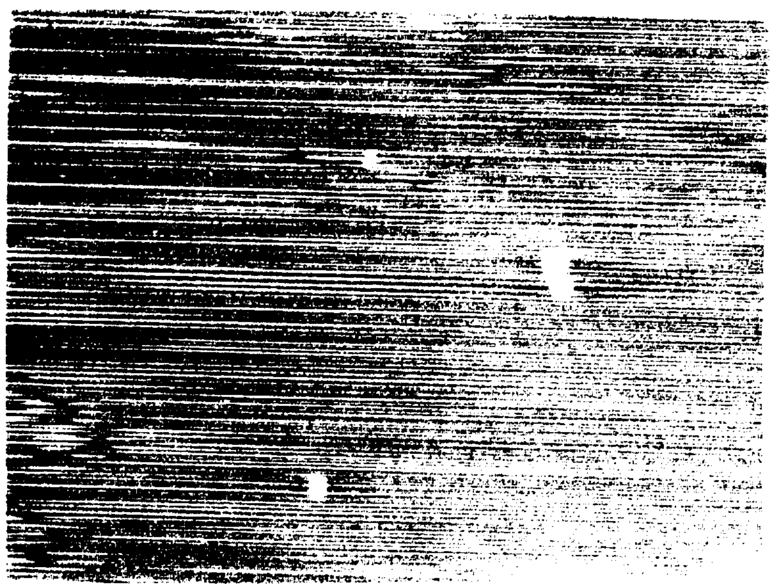
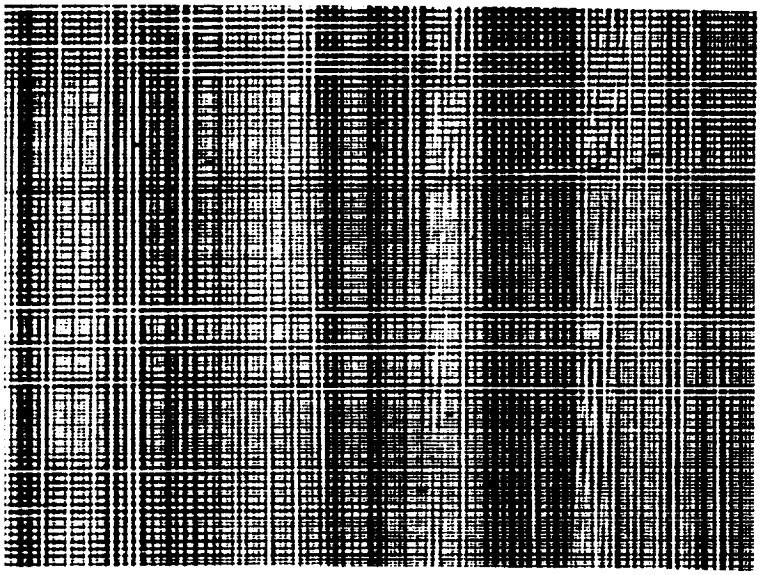


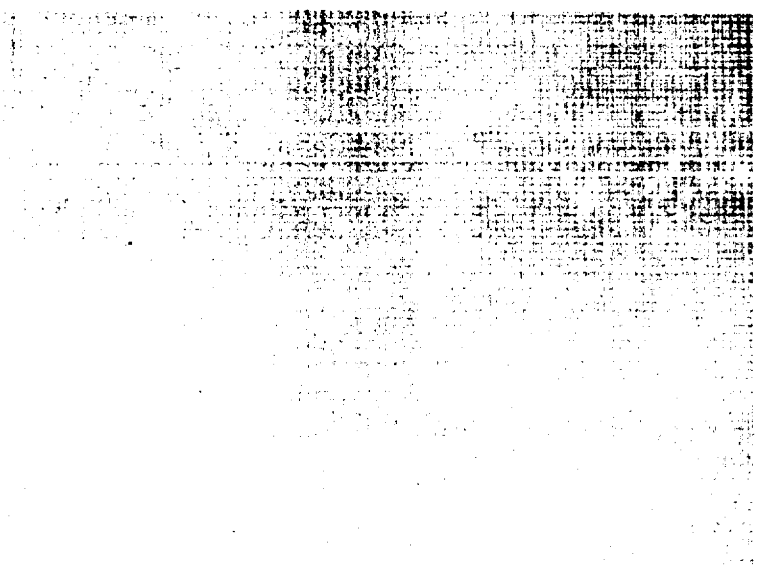
Figure 4. High Density Inclusions.
(Radiograph enlarged 8X.)

Note deformation of filaments in inclusion area.

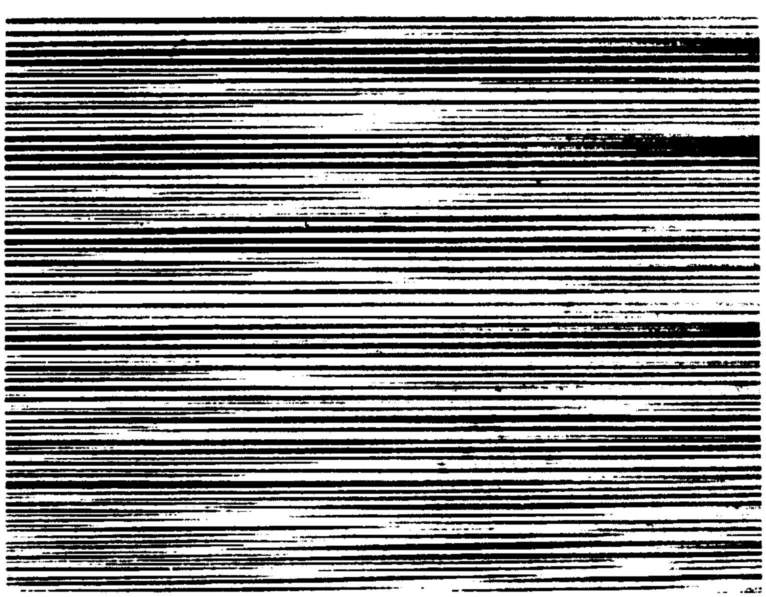
Figure 5. Filament Spacing Irregularities. (Radiographs enlarged 8X.)



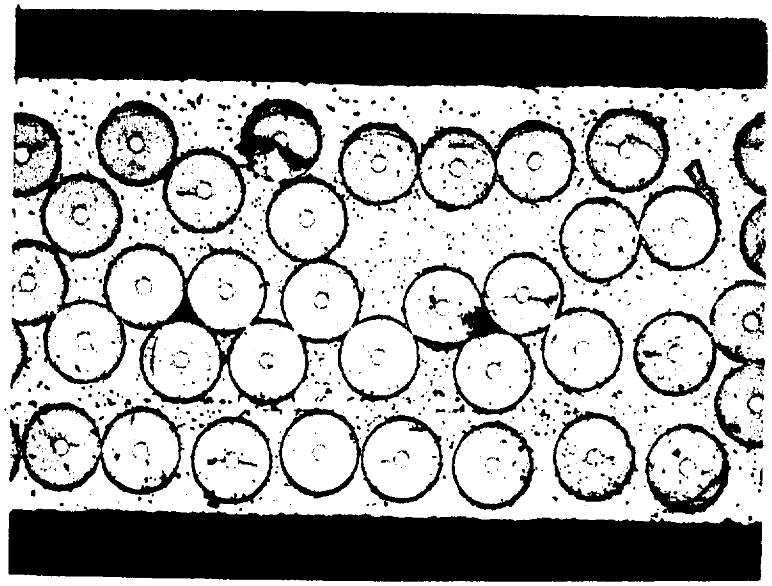
a. Zero to 90 crossply layup. Vertical filaments missing (filament gap). Also note crossover and moderate horizontal filament breakage.



b. Zero to 90 crossply layup. Filament gap up to 0.1 inch wide.



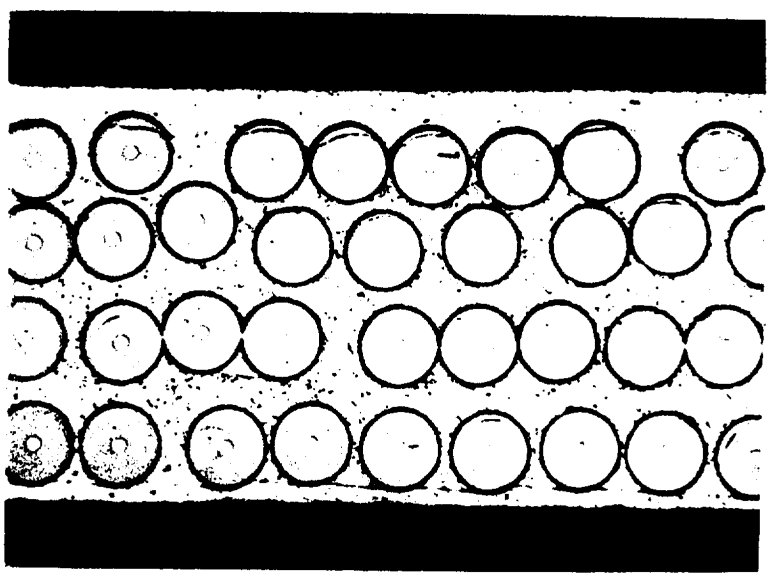
c. Unidirectional layup. Filament gaps.



C3574 100X

Figure 6. 6061 Aluminum - 50% Boron Composite, 0.0225 inch thick. (5 Al layers, 4 Boron, unidirectional layup, diffusion bonding process.)

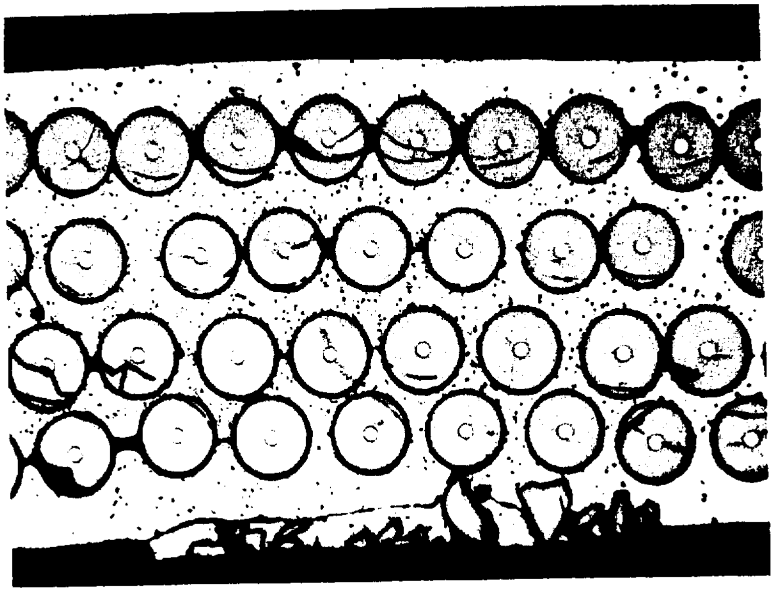
Analysis: Crossed-over boron filaments resulting in misspaced, cojoined filaments. Note adequate matrix diffusion bond even though adjacent filament layers are cojoined.



C3494 100X

Figure 7. 6061 Aluminum - 50% Boron Composite, 0.022 inch thick. (5 Al layers, 4 Boron; unidirectional layup, diffusion bonding process.)

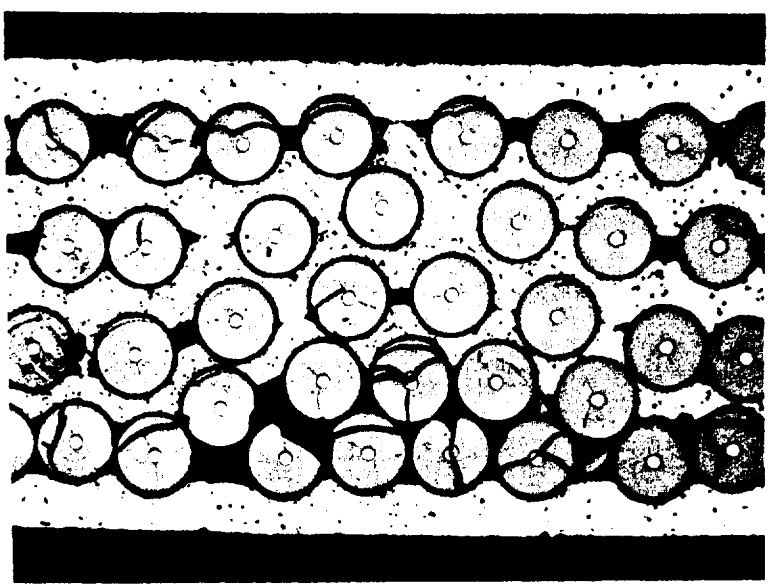
Analysis: Cojoined, improperly spaced filaments. Note adequate matrix diffusion bond. In this case cojoining is predominantly within filament layers.



C3491 100X

Figure 8. 6061 Aluminum - 50% Boron Composite, 0.024 inch thick. (5 Al layers, 4 Boron; unidirectional layup, diffusion bonding process.)

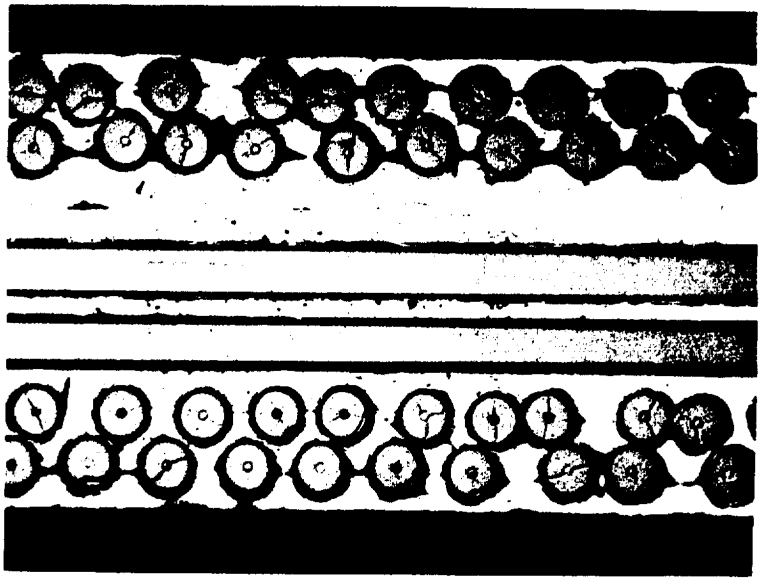
Analysis: Moderate matrix disbond with embedded Al-B splinter lower surface. Relatively normal nested filament array.



C3492 100X

Figure 9. 6061 Aluminum - 50% Boron Composite, 0.024 inch thick. (5 Al layers, 4 Boron; unidirectional layup, diffusion bonding process.)

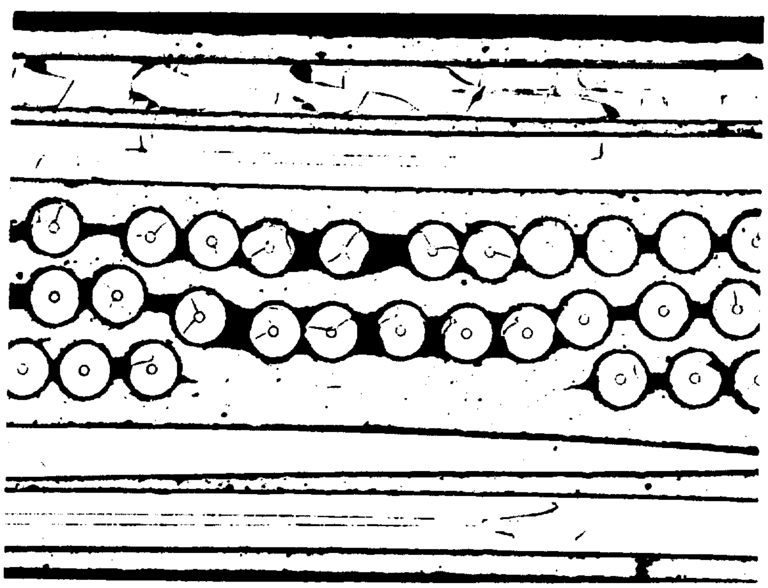
Analysis: Gross matrix disbond with crossed-over extra layer of filaments and irregular spacing.



C4427 75X

Figure 10. 6061 Aluminum - 50% Boron Composite, 0.031 inch thick. (Cross-ply layup, 2-3-2 Boron array, 8 Al layers; diffusion bonding process, transverse section.)

Analysis: Moderate-to-severe matrix disbond, upper longitudinal filaments. Moderate disbond lower filaments. Note matrix disbonding surrounding upper transverse filament. (Upper filament is not seen - section in that region through matrix only.)



C4427 75X

Figure 11. 6061 Aluminum - 50% Boron Composite, 0.037 inch thick. (Cross-ply layup, 2-3-2 Boron array, 8 Al layers; diffusion bonding process, longitudinal section.)

Analysis: Gross matrix disbond. Note 6 missing filaments in lower longitudinal filament layer.

GENERAL DYNAMICS
Convair Division

ATTACHMENT 1

Clarifications and/or Exceptions to Convair Aerospace Specification 0-00854:

Record Sheets: Acceptable except for exact time/temperature/pressure which are proprietary. Any deviation from Amercom standard conditions will be noted. Test data will include leached fiber bend tests.

1.2: Materials shall be: Type I, UD, Grade C, $53^{\pm 2}$ v/o; Type II crossply, Grade D, 49 to 52 v/o.

2.1 also 3.1.2: Presently available 6061 foils purchased from Alcoa to their 6061 spec will be used.

3.11: AMS 36CH not available to Amercom, however, 5.6 mil fiber of 500 ksi average strength as available from suppliers will be used.

3.3: All material will be delivered by Amercom in untrimmed or rough trimmed to oversize. Tolerance to be ± 10% on thin parts, ± 5% on thick parts.

3.4: Amercom feels a small amount of fiber breakage is typical of all diffusion bonded composite, in particular on high v/o crossply material. Concentrated filament breakage will constitute panel rejection.

3.5: Defects that degrade the properties or intended use of the panel justify rejection.

4.1: Convair will do all testing, with Amercom reserving the right to retest any material rejected.

4.4.2: For this program a lot will be defined as a panel.

GENERAL DYNAMICS
Convair Division
CODE IDENT NO.
14170

SPECIFICATION NO. 0-73547 | REV

DATE 1 November 1972

CONTRACT NO.

NO. OF PAGES 7

B. Sawing, Boron/Aluminum Composite,

Process Specification for

PROPOSAL ONLY

PREPARED BY ______________
D. M. Scannell

CHECKED BY ______________

APPROVED BY ______________
H. H. Rosenbaum

SPECIFICATION CHANGE NOTICES—INCORPORATED IN SPEC REVISIONS

SCN NO(S)	INCORP BY	CHECK BY	APPRVD BY	DATE	SPEC REV.	REVISION PACKAGE NO.		

INITIAL PACKAGE NO.			RELEASE	DOC	DISTR

FORM 6551

1. SCOPE

1.1 Scope. This specification establishes the requirements for the diamond disc sawing of boron/aluminum composite material conforming to Convair specification 0-00854.

1.2 Classification. The process covered by this specification shall be of one type and identified as 0-73547-1.

2. APPLICABLE DOCUMENTS

2.1 Unless otherwise specified herein, the following documents of the issue in effect on date of General Dynamics Convair Aerospace Division's request for quotation, form a part of this specification to the extent specified.

SPECIFICATIONS

Convair

0-00854	Sheet, Composite, Boron-Filament, Aluminum Alloy, Specification for

3. REQUIREMENTS

3.1 Drawing requirements. In the event of any conflict between the requirements of this specification and those specified in the engineering drawing, the requirements of the engineering drawing shall prevail.

3.2 Dimensions. Dimensions after cutting shall be within ±0.002 inch of the engineering drawing requirements.

PROPOSAL ONLY

3.3 Process materials and equipment. The following materials and equipment are required and shall be used in the performance of the process specified herein.

3.3.1 Material.

Fiberglass sheet

Aluminum sheet

3.3.2 Equipment.

Diamond disc cutoff saw, gantry-type

Cutoff blade, continuous rim, diamond impregnated, 46 grit size, 100 concentration, 1/4-inch depth

Diamond plated file

3.4 Procedures and operations.

3.4.1 Clean the surface of the work table of the cutoff saw with a suitable solvent and mount a test sheet of 0.060 inch to 0.090 inch thick aluminum or fiberglass on the work surface. Firmly clamp the test sheet in position. The test sheet should be longer in the cutting direction than the part to be sawed.

3.4.2 Set stops on the work surface of the saw to locate the part relative to the cutting blade.

3.4.3 Adjust the height of the cutting blade to give a cut into the test sheet 0.030 inch to 0.040 inch deep.

3.4.4 Turn on the cutting blade drive motor.

PROPOSAL ONLY

3.4.5 Turn on the coolant.

3.4.6 Engage the carriage traverse motor to the guide rack.

3.4.7 Adjust the carriage traverse motor speed control to give a cutting speed of 12 inches per minute.

3.4.8 Turn on the carriage traverse motor to feed the saw through the test sheet.

3.4.9 When the saw has completed the cut, disengage and turn off the carriage traverse motor.

3.4.10 Turn off the blade drive motor.

3.4.11 Turn off the coolant.

3.4.12 Measure the distance between the cut edge and the stops and verify that the dimension is correct. Adjust the stops if required.

3.4.13 Clean the surface of the test sheet and position the part against the stops. Firmly clamp it in place using suitable fixturing.

3.4.14 Repeat steps 3.4.4 through 3.4.6.

3.4.15 Adjust the carriage traverse motor speed to give the correct cutting speed for the thickness of the part. (See Figure 1)

3.4.16 Repeat operations 3.4.8 through 3.4.11.

3.4.17 Turn carriage traverse motor speed to 0.

3.4.18 Remove part from the work surface.

PROPOSAL ONLY

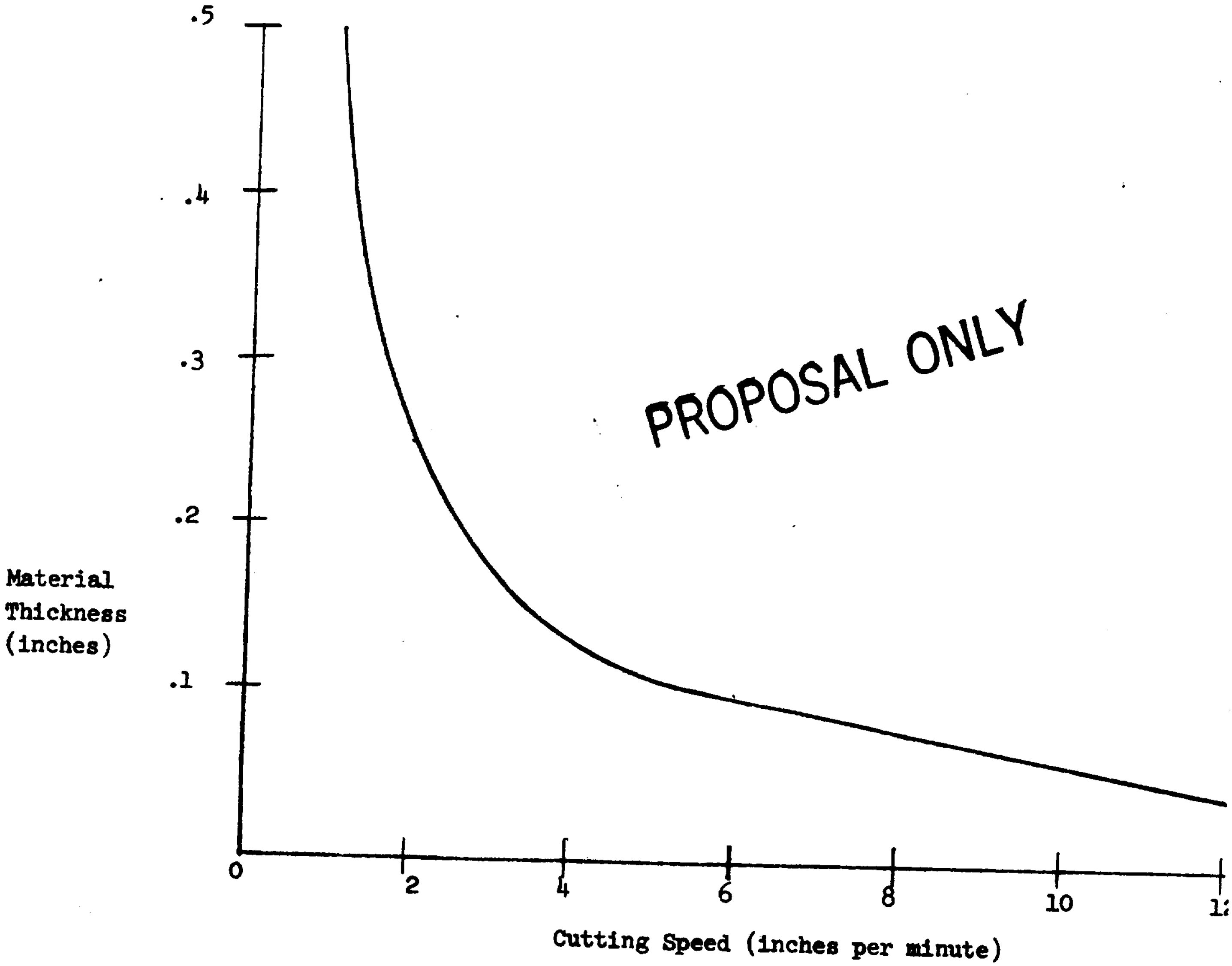


Figure 1. Cutting Rate for Boron/Aluminum

3.4.19 Wash the part with tap water and a mild detergent to remove the coolant. Dry with a clean cloth.

3.4.20 Check the dimensions of the part to ensure conformance to the engineering drawing requirements.

3.4.21 Deburr all cut edges using a diamond file.

4. QUALITY ASSURANCE PROVISIONS

4.1 Inspection and test responsibility. Unless otherwise specified in the contract or order, the supplier shall be responsible for the performance of all inspection and test requirements as specified herein. Except as otherwise specified, the supplier may use his own facilities or any commercial laboratory acceptable to Convair. Convair reserves the right to perform any of the inspections and tests set forth herein where deemed necessary to assure that the process conforms to the prescribed requirements.

4.2 Inspection records. Inspection records of examinations and tests shall be kept complete and available to Convair. These records shall contain all data necessary to determine compliance with the requirements of this specification.

4.3 Process control. Process controls, of a nature to assure performance of the process as specified herein, shall be established. Convair reserves the right to approve such controls where necessary to assure that the requirements of this specification have been or will be met on outside procurement.

4.4 Dimensions. All part dimensions shall be measured using any suitable method to assure adherence to the dimensions and tolerances specified.

5. PREPARATION FOR DELIVERY

Not applicable

PROPOSAL ONLY

6. NOTES

6.1 Intended use. The process described in this specification is intended for use in the manufacture of boron/aluminum components.

6.2 Ordering information. This specification number and its applicable revision letter or date shall be included in invitation for bid, contracts or purchase orders.

PROPOSAL ONLY

GENERAL DYNAMICS *Convair Division* CODE IDENT NO. 14170	SPECIFICATION NO. 0-13540	REV
	DATE 26 June 1972	
	CONTRACT NO.	

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PROPOSAL ONLY

NO. OF PAGES 7

C. Drilling, Boron/Aluminum Composite,

Specification for

PREPARED BY ____________
W. C. Braley

CHECKED BY ____________

APPROVED BY ____________
H. H. Rosenbaum

SPECIFICATION CHANGE NOTICES—INCORPORATED IN SPEC REVISIONS

SCN NO(S)	INCORP BY	CHECK BY	APPRVD BY	DATE	SPEC REV.	REVISION PACKAGE NO.		

INITIAL PACKAGE NO.			RELEASE	DOC	DISTR

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FORM 6551

PROPOSAL ONLY

GENERAL DYNAMICS
Convair Aerospace Division

0-73540

1. SCOPE

1.1 Scope. This specification establishes the requirements for the rotary ultrasonic diamond drilling of boron/aluminum composite material conforming to Convair Specification 0-00854.

1.2 Classification. The process covered by this specification shall be of one type and identified as 0-73540-1.

2. APPLICABLE DOCUMENTS

2.1 Unless otherwise specified herein, the following documents of the issue in effect on date of General Dynamics' Convair Aerospace Divisions request for quotation form a part of this specification to the extent specified.

SPECIFICATIONS

Convair

0-00854	Sheet, Composite, Boron-Filament, Aluminum Alloy, Specification for

3. REQUIREMENTS

3.1 Drawing requirements. In the event of any conflict between the requirements of this specification and those specified in the engineering drawing, the requirements of the engineering drawing shall prevail.

3.2 Dimensions. Hole tolerance shall be within +0.002 and -0.000 inch and the hole location shall satisfy the drawing requirements in all instances.

3.3 Process materials and equipment. The following materials and equipment are required and shall be used in the performance of the process specified herein.

3.3.1 Material

Fiberglass sheet

Aluminum plate

3.3.2 Equipment.

Branson Model UMT-3 Rotary ultrasonic machine tool (RUSM)

Branson Model J-17A power supply

Core drill, diamond impregnated, 180/270 grit size 100 concentration, tungsten power bond

Dial indicators

3.4 Procedures and operations.

3.4.1 Turn all switches on the RUSM to the off position.

3.4.2 Screw drill into spindle by hand and tighten with open end wrenches.

3.4.3 Check the run out of the tool using a dial indicator. The total deviation on the indicator should be less than 0.001 inch during a complete revolution of the drill.

3.4.4 Clean the work table of the machine with a suitable solvent and mount the part using suitable fixturing. An aluminum plate or fiberglass sheet should be placed between the specimen and the work table to protect the surface of the work table and minimize break out when the tool breaks through the specimen. If a drill template is to be used it should also be cleaned and mounted at this time.

3.4.5 Set the micro switch at the correct position so that the drill will retract automatically when it has gone through the part.

3.4.6 Locate the drill over the first hole location using dial indicators, template or scale, as required.

3.4.7 Adjust high pressure regulator to 55 psig.

3.4.8 Adjust low pressure regulator to 40 psig.

3.4.9 Turn main power switch on.

3.4.10 Turn motor switch on and turn motor speed control clockwise until correct spindle speed is obtained.

3.4.11 Turn coolant pump switch on.

3.4.12 Turn ultrasonics switch on.

CAUTION - DO NOT TURN ULTRASONICS SWITCH ON WHEN MOTOR SWITCH IS OFF.

3.4.13 Tune-in the drill with the J17A power supply.

3.4.13.1 Turn the power supply on by pushing the switch to the test position and hold.

3.4.13.2 Turn the metal tuning disc either clockwise or counterclockwise until the meter reaches its lowest reading. This should be from between 20-35. If while turning the disc in one direction the stop is reached, turn the disc in the other direction.

3.4.13.3 After the disc has been turned until the meter indicates the lowest value turn the disc clockwise until the needle rises one division on the meter scale.

3.4.13.4 Change the power supply switch from the test position to the ON position.

CAUTION - THE TUNING OPERATION SHOULD ALWAYS BE CARRIED OUT WITH THE SPINDLE ROTATING.

3.4.14 Turn auto feed switch to the ON position.

3.4.15 Turn hydraulic feed control to correct penetration rate, see Table I, as indicated on the dial indicator located to the left of the drilling head.

TABLE I. Drill Speed and Penetration Rate for Drilling B/Al

Material	Drill Speed sfm	Penetration Rate i.p.m.
Annealed B-Al	200-300	Up to 1.5
Solution treated and aged B-Al	150-250	Up to 0.3

3.4.16 When the hole is drilled and the drilling head has retracted, position the work piece so the drill is over the next hole location.

3.4.17 Turn auto feed switch to ON position.

3.4.18 Turn hydraulic feed control to correct penetration rate.

3.4.19 Repeat operations 3.4.14 through 3.4.18 until all holes are drilled.

3.4.20 Remove the work piece and deburr, if necessary.

4. QUALITY ASSURANCE PROVISION

4.1 Inspection and test responsibility. Unless otherwise specified in the contract or order, the supplier shall be responsible for the performance of all inspection and test requirements as specified herein. Except as otherwise specified, the supplier may use his own facilities or any commercial laboratory acceptable to Convair. Convair reserves the right to perform any of the inspections and tests set forth herein where deemed necessary to assure that the process conforms to the prescribed requirements.

4.2 Inspection records. Inspection records of examinations and tests shall be kept complete and available to Convair. These records shall contain all data necessary to determine compliance with the requirements of this specification.

4.3 Process control. Process controls, of a nature to assure performance of the process as specified herein, shall be established. Convair reserves the right to approve such controls where necessary to assure that the requirements of this specification have been or will be met on outside procurement.

4.4 Hole quality. All hole sizes and locations shall be measured using any suitable method to assure adherence to the tolerances specified.

5. PREPARATION FOR DELIVERY

Not applicable

6. NOTES

6.1 Intended use. The process described in this specification is intended for use in the manufacture of boron/aluminum components.

6.2 Ordering information. This specification number and its applicable revision letter or date shall be included in invitation for bid, contracts or purchase orders.

GENERAL DYNAMICS *Convair Division* CODE IDENT NO. 14170	SPECIFICATION NO. 0-73541	REV
	DATE 26 June 1972	
	CONTRACT NO.	

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PROPOSAL ONLY

D. Joining, Con Braz, Boron/

Aluminum Composite,

Specification for

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PREPARED BY W. C. Braley

APPROVED BY H. H. Rosenbaum

CHECKED BY

SPECIFICATION CHANGE NOTICES—INCORPORATED IN SPEC REVISIONS

SCN NO(S)	INCORP BY	CHECK BY	APPRVD BY	DATE	SPEC REV.	REVISION PACKAGE NO.		

INITIAL PACKAGE NO.			RELEASE	DOC	DISTR

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FORM 6551

1. SCOPE

1.1 Scope. This specification establishes the requirements for constructing structural parts by joining boron/aluminum composite to itself, to titanium alloy sheet or to aluminum alloy sheet, using the Con Braz joining process. This is a brazing process in which material is assemblied to a structural shape and brazed together by either low or high temperature brazing methods including furnace brazing and torch brazing.

1.2 Classification. The process covered by this specification shall be of one type and identified as 0-73541-1.

2. APPLICABLE DOCUMENTS

2.1 Unless otherwise specified herein, the following documents of the issue in effect on date of General Dynamics' Convair Aerospace Division request for quotation form a part of this specification to the extent specified.

SPECIFICATIONS

Federal

0-A-51	Acetone, Technical
0-H-765	Hydrochloric Acid
0-H-795	Hydrofluoric Acid Technical
0-N-350	Nitric Acid, Technical
0-S-598	Sodium Hydroxide, Technical
TT-M-261	Methyl ethyl Ketone

Military

MIL-Z-291	Zinc Oxide, Technical

Convair

0-00854	Sheet, Composite, Boron-Filament, Aluminum Alloy
0-73020	Deionized Water

3. REQUIREMENTS

3.1 Drawing requirements. In the event of any conflict between the requirements of the specification and those specified in the engineering drawing, the requirements of the engineering drawing shall prevail.

3.2 Process materials and equipment. The following materials and equipment are required and shall be used in the performance of the process specified herein.

3.2.1

Materials	Specification
Acetone	0-A-51
Methyl ethyl ketone	TT-M-261
Nitric Acid	0-N-350
Hydrofluoric acid	0-H-795
Hydrochloric acid	0-H-765

Materials	Specification
Sodium citrate	OSP
Sodium tartrate	USP
Sodium hydroxide	O-S-598
Zinc oxide	MIL-S-291
Deionized water	0-73020
Masking tape	See 6.3
Cheesecloth	DDD-C-301
Solder	See 6.3
Flux	See 6.3
Bristle brushes	See 6.3
Aluminum wire	See 6.3
Braze stop-off	See 6.3
Aluminum oxide cloth	See 6.3
Cleaner	See 6.3
Deoxidizer	See 6.3
Electroless nickel solution	See 6.3

3.2.2 Equipment

Con Braz Module

Radiant heat lamps

Brazing furnace

Oxygen-gas brazing torch

3.3 Procedures and operations.

3.3.1 Preliminary operations.

3.3.1.1 Install detail parts of the assembly in the brazing fixture and examine. Parts are suitable for plating and brazing only if areas to be joined are in intimate contact.

3.3.1.2 Remove detail parts from brazing fixture and mask the areas that do not require plating with a suitable heat and acid resistant masking tape.

3.3.1.3 Select two aluminum or titanium quality control specimens as applicable approximating 0.5 inch by 3 inches for testing the adhesion strength of the nickel plating.

3.3.1.4 Attach aluminum wires to the parts and control specimens to allow them to be supported in the cleaning and plating solutions.

3.3.2 Cleaning and electroless nickel plating.

3.3.2.1 Aluminum alloy and boron/aluminum parts. Clean and plate aluminum alloy and boron/aluminum parts as follows.

3.3.2.1.1 Solvent clean by wiping with cheesecloth and D-A-51 acetone or TT-M-261 methyl ethyl ketone.

3.3.2.1.2 Precondition by soaking for 30 minutes in a room temperature solution containing 16 ounces of deoxidizer per gallon of 0-73020 deionized water.

3.3.2.1.3 Rinse in cold tap water for one minute.

3.3.2.1.4 Immerse for one minute in a solution, at room temperature, containing eight ounces of cleaner per gallon of 0-73020 deionized water.

3.3.2.1.5 Rinse in cold tap water for one minute.

3.3.2.1.6 Immerse for 10 seconds in a solution of 3-5 percent 0-H-795 hydrofluoric acid, 40 percent 0-N-350 nitric acid, balance water.

3.3.2.1.7 Rinse in cold 0-73020 deionized water for one minute.

3.3.2.1.8 Zincate by immersing for 30 to 45 seconds, with agitation, in a room temperature solution containing 12 ounces of MIL-Z-291 zinc oxide and 65 ounces of 0-S-598 sodium hydroxide per gallon of 0-73020 deionized water.

3.3.2.1.9 Rinse in cold tap water for two minutes.

3.3.2.1.10 Immerse in a 50 percent 0-N-350 nitric acid solution, at room temperature for 10 seconds.

3.3.2.1.11 Rinse in cold tap water for one minute.

3.3.2.1.12 Repeat 3.3.2.1.8 and 3.3.2.1.9 above.

3.3.2.1.13 Immerse parts in electroless nickel plating solution at a temperature of 78°C to 82°C for 10 to 12 minutes. This will give a nickel thickness of 0.00020-inch to 0.00022 inch. If additional thickness is required, activate electroless nickel plate by immersion in 25 percent 0-N-765 hydrochloric acid at room temperature for 20 to 30 seconds prior to additional plating.

3.3.2.1.14 Rinse in cold tap water for one minute.

3.3.2.1.15 Rinse in cold 0-73020 deionized water for one minute.

3.3.2.1.16 Dry with a forced air flow.

3.3.2.1.17 Bake for 60 minutes at 325°F to 350°F.

3.3.2.2 Titanium alloy parts.

3.3.2.2.1 Solvent clean parts by wiping with chessecloth and 0-A-51 acetone or TT-M-261 methyl ethyl ketone.

3.3.2.2.2 Uniformly abrade surfaces to be plated using 150 or 220 grit aluminum oxide cloth.

3.3.2.2.3 Repeat 3.3.2.2.1 above.

3.3.2.2.4 Immerse for five minutes in a solution at 160°F containing 20 percent by weight of O-N-350 nitric acid, 10 percent by weight of sodium citrate or sodium tartrate and the balance 0-73020 deionized water.

3.3.2.2.5 Rinse in cold tap water for one minute.

3.3.2.2.6 Immerse in electroless nickel plating solution at a temperature of 78°C to 82°C for 10 to 12 minutes. This will give a nickel thickness of 0.00020 inch to 0.00022 inch. If additional thickness is required, activate electroless nickel plate by immersion in 25 percent hydrochloric acid at room temperature for 20 to 30 seconds prior to additional plating.

3.3.2.2.7 Rinse for two minutes in cold tap water.

3.3.2.2.8 Bake for 60 minutes at 900°F in a vacuum of 10^{-5} torr, or better.

3.3.2.2.9 Bend the aluminum or titanium quality control specimens to as tight a bend radii as possible and examine. Any peeling of the nickel plating shall cause rejection of the parts represented.

3.3.2.2.10 Check the nickel adhesion on the quality control specimens by cutting through the plating and attempting to remove it locally with adhesive backed masking tape. Any such removal shall cause rejection of parts represented.

3.3.3 Con Braz joining. Coat the part areas that do not require brazing with a braze strip-off compound (see 6.3) and after it has thoroughly dried apply the brazing flux as recommended for the solder used (see 6.3) to the joint areas. Solvent clean all brazing fixtures with cheesecloth and O-A-51 acetone or TT-M-261 methyl ethyl Ketone and install detail parts of the assembly with the joint areas in intimate contact for brazing by one of the following methods.

3.3.3.1 Con Braz module method.

3.3.3.1.1 Preplace solder (see 6.3) in the joint areas.

3.3.3.1.2 Feed assembly into the Con Braz module.

3.3.3.1.3 Turn on the extraction system and locate the duct adjacent to the braze area to ensure all fumes produced during joining are removed.

3.3.3.1.4 Set the power controller(s) to a previously determined value that will result in the part stabilizing at the brazing temperature for the alloy being used.

3.3.3.1.5 Observe the assembly as it is heating to the brazing temperature at which time the braze alloy will melt to form fillets at the joint area(s). Any areas deficient in braze alloy should be brazed manually with a prefluxed solder rod.

3.3.3.1.6 Feed the assembly through the Con Braz module at a rate that is consistent with production of a good part.

3.3.3.1.7 When the assembly is completely joined turn the power off and allow it to cool in the fixture to 200°F or less.

3.3.3.2 Furnace brazing method.

3.3.3.2.1 Preplace solder (see 6.3) at the joint area(s). Place the assembly in a furnace at the brazing temperature and allow to soak for a predetermined period of time dependent upon the fixture mass, the assembly size and mass and the brazing temperature.

3.3.3.2.2 Remove assembly from the furnace and allow to cool to 200 F, or less.

3.3.3.3 Torch brazing method.

3.3.3.3.1 Heat the joint area to the brazing temperature using either radiant quartz lamps or an oxygen-gas torch.

3.3.3.3.2 When the assembly reaches the brazing temperature feed the prefluxed braze alloy in to the joint area to produce a joint of uniform, good quality. Feed the braze alloy in to both sides of the joint(s).

3.3.3.3.3. Turn off the torch and allow the assembly to cool to 200°F, or less.

3.3.4 Cleaning. Remove brazed assembly from fixture and wash in hot water using a bristle brush to remove flux residue.

3.3.5 Joint quality. Joint quality, permissible defects and method(s) of inspection shall be as agreed upon by purchaser and vendor.

3.3.6 Toxic or hazardous formulations. Some of the materials listed in 3.2 are toxic or hazardous to varying degrees, as indicated on material containers. All required safety precautions shall be exercised under the surveillance of the cognizant safety personnel.

4. QUALITY ASSURANCE PROVISIONS

4.1 Inspection and test responsibility. Unless otherwise specified in the contract or order, the supplier shall be responsible for the performance of all inspection and test requirements as specified herein. Except as otherwise specified, the supplier may use his own facilities or any commercial laboratory acceptable to Convair. Convair reserves the right to perform any of the inspections and tests set forth herein where deemed necessary to assure that the process conforms to the prescribed requirements.

4.2 Inspection records. Inspection records of examinations and tests shall be kept complete and available to Convair. These records shall contain all data necessary to determine compliance with the requirements of this specification.

4.3 Process control. Process controls, of a nature to assure performance of the process as specified herein, shall be established. Convair reserves the right to approve such controls where necessary to assure the requirements of this specification have been or will be met on outside procurement.

4.3.1 Inspection during process. Inspection personnel shall conduct frequent and regular inspections to ensure that the materials, process preparation, procedures, and controls are in compliance with the requirements of this specification.

4.3.2 Test methods and inspection criteria. See 3.3.5.

5. PREPARATION FOR DELIVERY

Not applicable.

6. NOTES

6.1 Intended use. The prcess described by this specification is intended for use in the fabrication of boron/aluminum composite structural parts by brazing.

6.2 Ordering information. This specification number and its applicable revision letter or date shall be included in invitations for bid, contracts or purchase order.

6.3 Suitable materials. The following materials have been found suitable for brazing per this specification. Use of alternate materials should be in accordance with manufacturers instructions for concentration, time, temperature, etc.

Aluminum oxide cloth	commercial grade
Masking tape	commercial grade
Bristle brushes	" "
Aluminum wire	" "
Braze stop-off	Nicrobraze Red Wall Colmony Corp. 19345 John R Street Detroit, Mich. 48203
Solder (up to 300°F)	Allstate Alloy 105 All-State Welding Alloys Co. P. O. Box 350, White Plains, N. Y. 10602
Solder (300°-600°F)	Alloy 380-1 Ney Metals, Inc. 269 Freeman St. Brooklyn, N. Y.

Aluminum cleaner	Aluminetch No. 2 Purex Corporation Ltd. Turco Products Inc., Division 24600 S. Main St. Washington, CA 90746
Deoxidizer	LP-3AL-13 Allied Research Products Division of the Richardson Co. 1250 N. Main St. Los Angeles, CA 90012
Electroless nickel solution	Anomet 24 Anomet, Inc. 1132 S. Prarie Unit 8 Hawthorn, CA

APPENDIX B

MECHANICAL PROPERTY DATA

This appendix contains the mechanical property data recorded on the program during Phase II, Material Evaluation. Table B-1 contains data on unidirectional B/Al and Table B-2 contains data on ±45° cross-plied B/Al.

Table B-1. Mechanical Properties of B/Al Composite Material (Unidirectional Layup)

Panel No.	Test Temp. °K	Test Temp. (°F)	Direction	Tensile Strength MN/m²	Tensile Strength (ksi)	Tensile Modulus GN/m²	Tensile Modulus (msi)	Strain to Failure μm/m	Poisson's Ratio	Shear Strength MN/m²	Shear Strength (ksi)	Compression Strength MN/m²	Compression Strength (ksi)	Compression Modulus GN/m²	Compression Modulus (msi)	Poisson's Ratio	Notched Tensile Strength MN/m²	Notched Tensile Strength (ksi)
ME-1 (51.2v/o)	297	(75)	Long.	1524	221	267	38.7	6700		124	18.0	2006	291	278	40.4		1027	149
				1662	241	243	35.2	8100		169	24.5	2137	310	273	39.6		1179	171
				1648	239	227	32.9	7200		167	24.2	2372	344	259	37.6		1000	145
				1586	230	220	31.9	7700		171	24.8	2344	340	256	37.2		945	137
				1317	191	216	31.3	6600	0.26	172	25.0	1648	239	270	39.2		938	136
				1551	225	215	31.2	7500	-	126	18.3	-	-	283	41.0		1110	161
				1548	225	231	33.5	7300	0.26	155	22.5	2101	305	270	39.2		1033	150
			Trans.	140	20.3	136	19.7	6100				304	44.1	192	27.8			
				139	20.1	117	17.0	5600				308	44.6	112	16.2			
				150	21.7	130	18.9	7600				265	38.4	206	29.8			
				159	23.1	160	23.2	6800				294	42.6	192	27.8			
				144	20.9	138	20.0	3700				284	41.2	166	24.0			
				159	23.1	153	22.2	5000	0.17			254	36.8	154	22.4	0.18		
				149	21.5	139	20.2	5800	0.17			285	41.3	170	24.7	0.18		
	77	(-320)	Long.	1407	204	212	30.8	7200		145	21.0	2186	317	293	42.5		566	82.5
				1544	224	210	30.5	7800	0.26	173	25.1	1731	251	296	43.0		855	124
				1476	214	211	30.7	7500	0.26	159	23.1	1959	284	295	42.8		711	103
			Trans.	172	24.9	132	19.1	2800				427	62.0	152	22.0			
				225	32.6	163	23.6	4800	0.12			387	56.1	160	23.2	0.13		
				199	28.8	148	21.4	3800	0.12			407	59.1	156	22.6	0.13		
	477	(400)	Long.	1220	177	216	31.3	5700	0.20	71	10.3	1317	191	296	43.0		1248	181
				1613	234	216	31.3	8300	-	79	11.5	1689	245	263	38.1		1055	153
				1417	206	216	31.3	7000	0.20	75	10.9	1503	218	280	40.6		1152	167
			Trans.	160	23.2	114	16.5	2500	0.08			205	29.7	166	24.0			
				126	18.3	101	14.6	1900	-			212	30.8	169	24.5			
				143	20.8	108	15.6	2200	0.08			209	30.3	168	24.3			
	589	(600)	Long.	1200	174	203	29.5	5900	0.13	61	8.8	1124	163	167	24.2		1055	153
				1248	181	201	29.2	6400	-	66	9.6	1269	184	186	27.0		1179	171
				1224	178	202	29.4	6200	0.13	64	9.2	1197	174	177	25.6		1117	162
			Trans.	55	8.1	62	9.1					103	14.9	99	14.4			
				54	8.0	69	10.0					106	15.4	72	10.5			
				55	8.1	66	9.6					105	15.2	86	12.5			
	700	(800)	Long.	1076	156	-	-			27	3.9	765	111	177	25.6		1138	165
				1027	149	172	25.0		0.16	34	5.0	814	118	148	21.4		1048	152
				1052	153	172	25.0		0.16	31	4.5	790	115	163	23.5		1093	159
			Trans.	26	3.7	-	-					62	9.0	67	9.7			
				36	5.2	67	9.7					42	6.1	115	16.6			
				31	4.5	67	9.7					52	7.6	91	13.2			
ME-2 (51.0v/o)	297	(25)	Long.	1482	215	195	28.3	6300		103	15.0	1882	273	239	34.6		1020	148
				1634	237	188	27.3	8300		156	22.6	2220	322	298	43.2		1200	174
				1289	187	184	26.7	8400		201	29.2	1731	251	277	40.2		1069	155
				1434	208	199	28.9	7400		127	18.4	2006	291	302	43.8		938	136
				1345	195	226	32.8	6300		239	34.7	1600	232	255	37.0		965	140
				1503	218	208	30.2	7100	0.24	194	28.2	-	-	255	37.0		993	144
				1448	210	200	29.0	7300	0.24	170	24.7	1888	274	271	39.3		1031	150

Table B-1. Mechanical Properties of B/Al Composite Material, Contd (Unidirectional Layup)

Panel No.	Test Temp. °K	Test Temp. (°F)	Direction	Tensile Strength MN/m²	Tensile Strength (ksi)	Tensile Modulus GN/m²	Tensile Modulus (msi)	Strain to Failure μm/m	Poisson's Ratio	Shear Strength MN/m²	Shear Strength (ksi)	Compression Strength MN/m²	Compression Strength (ksi)	Compression Modulus GN/m²	Compression Modulus (msi)	Poisson's Ratio	Notched Tensile Strength MN/m²	Notched Tensile Strength (ksi)
ME-2 (51.0 v/o) Cont'd	297	(25)	Trans.	129	18.7	139	20.1	2400				265	38.4	158	22.9			
				139	20.1	141	20.5	5800				274	39.8	198	28.7			
				123	17.8	163	23.7	4000				257	37.2	-	-			
				125	18.1	146	21.1	7200				254	36.8	-	-			
				153	22.2	140	20.3	4100				251	36.4	179	26.0			
				128	18.6	130	18.9	1600	0.11			265	38.4	162	23.5	0.18		
				133	19.3	143	20.8	4200	0.11			261	37.8	174	25.3	0.18		
	77	(-320)	Long.	1331	193	209	30.3	7000		169	24.5	2055	298	236	34.2		1055	153
				1554	224	209	30.3	8000	0.23	137	19.8	1393	202	-	-		635	92.6
				1438	209	209	30.3	7500	0.23	153	22.2	1724	250	236	34.2		845	123
			Trans.	155	22.5	181	26.3	1900				407	59.0	128	18.6			
				181	26.2	132	19.1	3800	0.11			428	62.1	171	24.8			
				168	24.4	157	22.7	2900	0.11			418	60.6	150	21.7			
	477	(400)	Long.	1303	189	248	35.9			99	14.3	1648	239	186	27.0		1124	163
				1469	213	200	29.0	7200		103	15.0	1827	265	197	28.6		1193	173
				1386	201	224	32.5	7200		101	14.7	1738	252	192	27.8		1159	168
			Trans.	88	12.8	63	9.1					199	28.8	159	23.1			
				84	12.2	94	13.6					171	24.8	-	-			
				86	12.5	79	11.4					185	26.8	159	23.1			
	589	(600)	Long.	1400	203	201	29.2			38	5.5	1117	162	168	24.4		1234	179
				1413	205	156	22.6			75	10.8	883	128	190	27.6		1172	170
				1407	204	179	25.9			57	8.2	1000	145	179	26.0		1203	175
			Trans.	56	8.1	57	8.2					110	16.0	90	13.0			
				50	7.3	126	18.2					85	12.3	150	21.7			
				53	7.7	92	13.2					98	14.2	120	17.4			
	700	(800)	Long.	1131	164	194	28.1			62	9.0	550	79.7	99	14.4		1062	154
				1255	182	210	30.5			35	5.1	452	65.7	141	20.4		1103	160
				1193	173	202	29.3			49	7.1	501	72.7	120	17.4		1083	157
			Trans.	28	4.1	90	13.1					61	8.8	85	12.-			
				32	4.7	37	5.3					53	7.7	-	-			
				30	4.4	64	9.2					57	8.3	85	12.3			
ME-3 (50.6 v/o)	297	(75)	Long.	1510	219	194	28.2	7300		243	35.3	1903	276	252	36.6		958	139
				1565	227	201	29.2	8500		226	32.8	1662	241	-	-		958	139
				1675	243	198	28.7	8500		197	28.6	1579	229	284	41.2		1014	147
				1703	247	194	28.2	9000		133	19.3	1751	254	275	39.9		958	139
				1496	217	219	31.7	7400		104	15.1	1717	249	255	37.0		855	124
				1558	226	217	31.5	7800	0.19	129	18.7	1944	282	230	33.4		752	109
				1585	230	204	29.6	8100	0.19	172	25.0	1759	255	259	37.6		916	133
			Trans.	156	22.6	103	15.0	6700				310	45.0	204	29.6			
				134	19.4	118	17.1	7400				274	39.8	-	-			
				134	19.4	152	22.0	6800				249	36.1	160	23.2			
				142	20.6	150	21.7	3000				274	39.7	119	17.3			
				118	17.1	141	20.4	1700	0.12			292	42.4	159	23.1	0.09		
				137	19.8	133	19.2	5100	0.12			285	41.4	148	21.4	-		
												281	40.7	158	22.9	0.09		

Table B-1. Mechanical Properties of B/Al Composite Material, Contd (Unidirectional Layup)

Panel No.	Test Temp. °K	Test Temp. (°F)	Direction	Tensile Strength MN/m²	Tensile Strength (ksi)	Tensile Modulus GN/m²	Tensile Modulus (msi)	Strain to Failure μm/m	Poisson's Ratio	Shear Strength MN/m²	Shear Strength (ksi)	Compression Strength MN/m²	Compression Strength (ksi)	Compression Modulus GN/m²	Compression Modulus (msi)	Poisson's Ratio	Notched Tensile Strength MN/m²	Notched Tensile Strength (ksi)
ME-3 (50.6 v/o) Cont'd	77	(-320)	Long.	1503	218	207	30.0	7900		182	26.4	1979	287	-	-		724	105
				1662	241	209	30.3	7000	0.32	167	24.2	1882	273	266	38.6		674	97.7
				1583	230	208	30.2	7500	0.32	175	25.3	1931	280	266	38.6		699	101
			Trans.	173	25.1	160	23.2	2200				452	65.6	160	23.2			
				166	24.0	161	23.3	1900	0.12			426	61.8	-	-			
				170	24.6	161	23.3	2100	0.12			439	63.7	160	23.2			
	477	(400)	Long.	1662	241	183	26.5	8300		115	16.7	1634	237	186	27.0		1269	184
				1496	217	174	25.3	6900		113	16.4	1448	210	192	27.8		1262	183
				1579	229	179	25.9	7600		114	16.6	1541	224	189	27.4		1266	184
			Trans.	130	18.8	95	13.8					226	32.7	159	23.1			
				143	20.7	105	15.2					219	31.7	172	25.0			
				137	19.8	100	14.5					223	32.2	166	24.1			
	589	(600)	Long.	1441	209	258	37.4			53	7.7	1124	163	166	24.1		1110	161
				1289	187	174	25.3			57	8.2	1103	160	155	22.5		1186	172
				1365	198	216	31.4			55	8.0	1114	162	161	23.3		1148	167
			Trans.	86	12.4	49	7.1					110	15.9	91	13.2			
				67	9.7	75	10.8					110	15.9	-	-			
				77	11.1	62	9.0					110	15.9	91	13.2			
	700	(800)	Long.	1413	205	179	25.9			30	4.3	442	64.2	157	22.8		1000	145
				1165	169	219	31.8			30	4.3	560	81.7	146	21.2		1083	157
				1289	187	199	28.9			30	4.3	501	73.0	152	22.0		1042	151
			Trans.	28	4.1	69	10.0					55	7.9	72	10.4			
				33	4.8	41	5.9					59	8.6	89	12.9			
				31	4.5	55	8.0					57	8.3	81	11.7			
ME-4 (48.9 v/o)	297	(75)	Long.	1565	227	250	36.3	6500		111	16.1	1986	288	228	33.0		1034	150
				1324	192	228	33.1	6800		89	12.9	1855	269	292	42.4		869	126
				1427	207	224	32.5	6600		175	25.4	1910	277	-	-		958	139
				1607	233	226	32.8	7000		199	28.8	1496	217	214	31.0		674	98
				1372	199	215	31.2	6700		89	12.9	2013	292	230	33.4		979	142
				1648	239	212	30.7	8200	0.22	126	18.2	2406	349	230	33.4		972	141
				1491	216	226	32.8	7000	0.22	132	19.1	1944	282	239	34.6		914	133
			Trans.	88	12.8	137	19.9	6700				313	45.4	110	15.9			
				90	13.1	121	17.6	7300				297	43.0	130	18.8			
				108	15.7	112	16.3	5900				282	40.9	128	18.5			
				119	17.3	151	21.9	5700				281	40.7	217	31.4			
				100	14.5	86	12.5	6900				297	43.1	159	23.1	0.07		
				103	15.0	88	12.8	8500	0.13			264	38.3	172	25.0	-		
				101	14.7	116	16.8	6800	0.13			289	41.9	153	22.1	0.07		

Table B-1. Mechanical Properties of B/Al Composite Material, Contd (Unidirectional Layup)

Panel No.	Test Temp. °K	Test Temp. (°F)	Direction	Tensile Strength MN/m²	Tensile Strength (ksi)	Tensile Modulus GN/m²	Tensile Modulus (msi)	Strain to Failure μm/m	Poisson's Ratio	Shear Strength MN/m²	Shear Strength (ksi)	Compression Strength MN/m²	Compression Strength (ksi)	Compression Modulus GN/m²	Compression Modulus (msi)	Poisson's Ratio	Notched Tensile Strength MN/m²	Notched Tensile Strength (ksi)
ME-5 (48.7 v/o)	297	(75)	Long.	1365	198	218	31.6	5000		151	21.9	1889	274	246	35.6		1069	155
				1476	214	218	31.6	7000		161	23.3	2399	348	214	31.0		1207	175
				1317	191	192	27.9	6100		172	24.9	2475	359	-	-		1193	173
				1220	177	214	31.0	6300		115	16.7	1455	211	298	43.2		1076	156
				1448	210	223	32.3	7000		133	19.3	2089	303	230	33.4		1138	165
				1393	201	211	30.6	6900	0.22	156	22.6	1993	289	247	35.8		1131	164
				1370	199	213	30.8	6400	0.22	148	21.5	2050	297	247	35.8		1136	165
			Trans.	148	21.5	141	20.5	7200				314	45.5	126	18.3			
				149	21.6	182	26.4	7900				311	45.1	170	24.6			
				137	19.8	172	24.9	4500				317	45.9	149	21.6			
				126	18.3	130	18.9	9100				310	45.0	168	24.4			
				135	19.6	120	17.4	7400				283	41.0	150	21.8	0.08		
				174	25.3	141	20.4	4300	0.06			321	46.6	170	24.6	-		
				145	21.0	148	21.6	6700	0.06			309	44.9	156	22.6	0.08		

Table B-2. Mechanical Properties of B/Al Composite Material (±45° Crossplied Layup)

Panel No.	Test Temp. °K	Test Temp. (°F)	Tensile Strength MN/m²	Tensile Strength (ksi)	0.2% Yield Strength MN/m²	0.2% Yield Strength (ksi)	Tensile Modulus GN/m²	Tensile Modulus (msi)	Strain to Failure μm/m	Poisson's Ratio	Compression Strength MN/m²	Compression Strength (ksi)	Compression Modulus GN/m²	Compression Modulus (msi)	Poisson's Ratio
MEX-1	297	(75)	213	30.9	121	17.5	132	19.1	25,000		378	55.0	140	20.3	
(47.8v/o)			228	33.1	122	17.7	65	9.5	21,000		412	59.8	193	28.0	
			206	29.9	133	19.3	102	14.8	15,000		422	61.4	86	12.4	
			208	30.1	126	18.2	93	13.5	15,000		412	59.8	199	28.9	
			283	40.9	131	19.0	110	16.0	-		579	84.1	142	20.6	
			194	28.2	124	18.0	110	16.0	-	0.32	366	53.2	152	22.0	0.25
			222	32.2	126	18.3	102	14.8	19,000	0.32	428	62.2	152	22.0	0.25
	77	(-320)	192	27.8	145	21.0	76	11.0	9,000		645	93.7	139	20.1	
			197	28.6	130	18.8	126	18.2	10,000	0.43	696	101	153	22.2	
			195	28.2	138	19.9	101	14.6	9,500	0.43	671	97.4	146	21.2	
	477	(400)	273	39.6	143	20.8	90	13.1	67,000		487	70.6	106	15.4	
			232	33.7	139	20.2	127	18.4	56,000	0.56	551	79.9	109	15.8	
			253	36.7	141	20.5	109	15.8	61,500	0.56	519	75.3	108	15.6	
	589	(600)	146	21.1	76	11.0	76	11.0	60,000		192	27.9	103	14.9	
			117	17.0	70	10.2	81	11.8	-		-	-	-	-	
			132	19.1	73	10.6	79	11.4	60,000		192	27.9	103	14.9	
	700	(800)	99	14.3	33	4.8	70	10.2	76,000		132	19.2	81	11.7	
			92	13.3	-	-	62	9.0	-		106	15.3	72	10.4	
			96	13.8	33	4.8	66	9.6	76,000		119	17.3	77	11.1	
MEX-2	297	(75)	229	33.2	110	16.0	98	14.2	25,000		567	82.3	109	15.8	
(48.4v/o)			249	36.1	128	18.6	115	16.7	24,000		703	102	161	23.3	
			263	38.1	123	17.9	145	21.0	29,000		632	91.9	128	18.6	
			247	35.8	126	18.3	123	17.8	27,000		430	62.4	123	17.9	
			212	30.8	125	18.1	123	17.8	-		545	79.1	86	12.5	0.40
			248	36.0	124	18.0	101	14.7	-	0.43	551	79.9	129	18.7	-
			241	35.0	123	17.8	117	17.0	26,000	0.43	571	82.9	123	17.8	0.40
	77	(-320)	243	35.3	145	21.0	115	16.7			527	76.5	132	19.2	
			258	37.4	142	20.6	115	16.7		0.33	681	98.8	-	-	
			251	36.4	144	20.8	115	16.7		0.33	604	87.7	132	19.2	
	477	(400)	236	34.2	159	23.0	90	13.0	48,000		441	64.0	152	22.0	
			199	28.8	171	24.8	115	16.6	40,000		416	60.3	175	25.4	
			218	31.5	165	23.9	102	14.8	44,000		429	62.2	164	23.7	
	589	(600)	152	22.0	75	10.9	75	10.9	71,000		266	38.5	145	21.0	
			139	20.2	69	10.0	69	10.0	65,000		177	25.6	67	9.8	
			146	21.1	72	10.5	72	10.5	68,000		222	32.1	106	15.4	
	700	(800)	101	14.6	-	-	-	-	66,000		96	13.9	70	10.2	
			55	8.0	28	4.1	61	8.9	72,000		93	13.5	117	17.0	
			78	11.3	28	4.1	61	8.9	69,000		95	13.7	94	13.6	

Table B-2. Mechanical Properties of B/Al Composite Material, Contd (±45° Crossplied Layup)

Panel No.	Test Temp. °K	Test Temp. (°F)	Tensile Strength MN/m²	Tensile Strength (ksi)	0.2% Yield Strength MN/m²	0.2% Yield Strength (ksi)	Tensile Modulus GN/m²	Tensile Modulus (msi)	Strain to Failure μ m/m	Poisson's Ratio	Compression Strength MN/m²	Compression Strength (ksi)	Compression Modulus GN/m²	Compression Modulus (msi)	Poisson's Ratio
MEX-3 (47.7 v/o)	297	(75)	248	35.9	126	18.3	154	22.4	28,000		452	65.5	123	17.9	
			219	31.7	115	16.7	130	18.9	25,000		434	63.1	-	-	
			239	34.7	115	16.6	167	24.2	23,000		463	67.2	125	18.1	
			243	35.3	97	14.1	103	15.0	29,000		385	55.9	119	17.2	
			237	34.3	128	18.5	75	10.9	-		445	64.7	159	23.0	0.24
			228	33.1	120	17.4	143	20.8	-	0.68	528	76.6	159	23.1	-
			236	34.2	117	16.9	129	18.7	26,000	0.68	451	65.5	137	19.9	0.24
	77	(-320)	245	35.5	123	17.8	136	19.7	14,800		497	72.1	102	14.8	
			226	32.7	137	19.8	125	18.1	-		620	90.1	193	28.0	
			236	34.1	130	18.8	131	18.9	14,800		559	81.1	148	21.4	
	477	(400)	279	40.4	156	22.6	136	19.7	53,000		438	63.7	83	12.0	
			221	32.1	166	24.0	103	15.0	-		385	55.8	150	21.7	
			250	36.3	161	23.3	120	17.4	53,000		412	59.8	117	16.9	
	589	(600)	146	21.1	77	11.1	69	10.0	56,000		289	42.0	116	16.8	
			98	14.2	49	7.2	67	9.7	-	0.80	186	26.9	58	8.4	
			122	17.7	63	9.2	68	9.9	56,000	0.80	238	34.5	87	12.6	
	700	(800)	98	14.2	-	-	-	-	-		116	16.8	101	14.6	
			113	16.4	47	6.8	72	10.4	68,000		92	13.3	72	10.5	
			106	15.3	47	6.8	72	10.4	68,000		104	15.1	87	12.6	
MEX-4 (47.9 v/o)	297	(75)	239	34.6	119	17.2	141	20.4	22,000		632	91.7	167	24.0	
			241	34.9	115	16.6	147	21.3	21,000		429	62.4	181	26.3	
			233	33.8	117	16.9	108	15.6	22,000		411	59.7	97	14.0	
			232	33.7	118	17.1	110	16.0	20,000		582	84.5	99	14.4	
			248	36.0	116	16.8	143	20.8	-	0.70	479	69.7	138	20.0	0.33
			270	39.1	117	17.0	126	18.2	-	-	569	82.6	153	22.2	-
			244	35.4	117	16.9	129	18.7	21,000	0.70	517	75.1	139	20.2	0.33
MEX-5 (50.1 v/o)	297	(75)	327	47.4	93	13.5	90	13.1	34,000		456	66.2	143	20.7	
			306	44.4	106	15.3	90	13.1	35,000		539	78.3	115	16.6	
			287	41.6	119	17.3	130	18.9	27,000		606	88.8	109	15.8	
			310	45.0	112	16.2	129	18.7	33,000		557	81.0	179	25.9	
			300	43.4	107	15.5	86	12.5	-	0.25	500	72.8	138	20.0	0.25
			289	41.9	110	16.0	115	16.7	-	-	603	87.4	169	24.5	-
			303	44.0	108	15.6	107	15.5	32,000	0.25	544	79.1	142	20.6	0.25